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# SCIENCE



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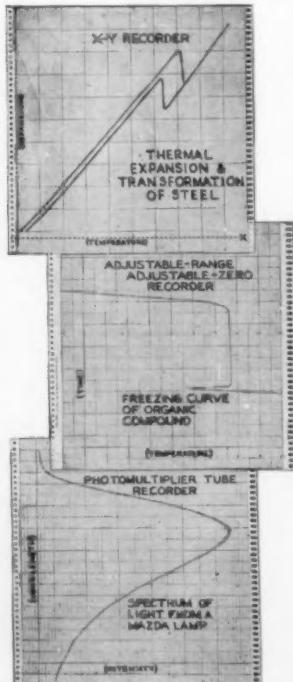
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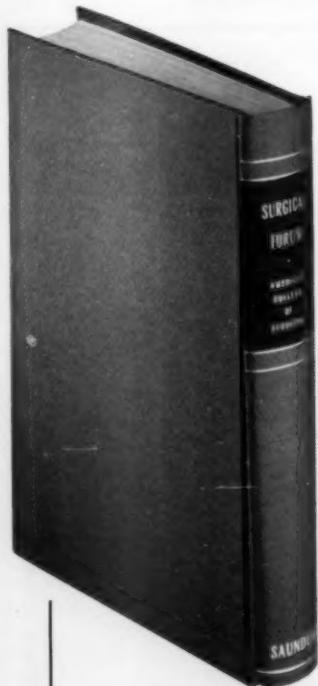
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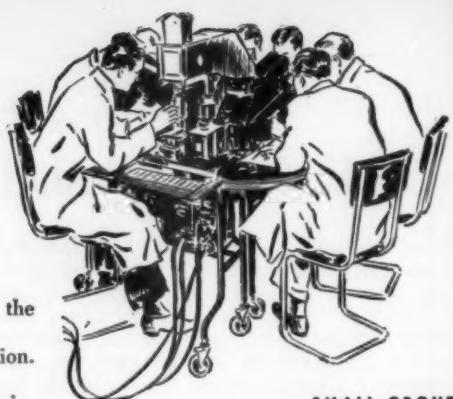
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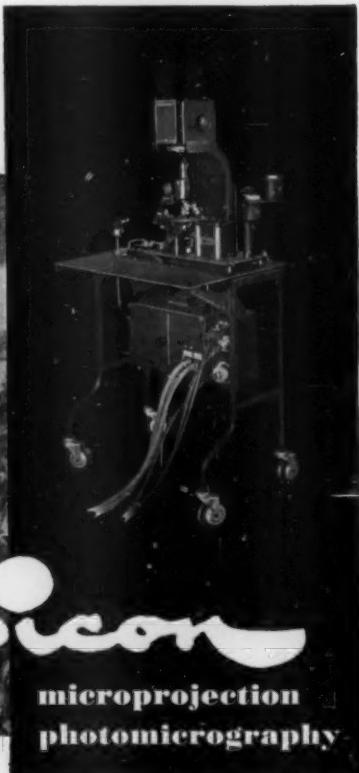
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RECENT progress in physics has been marked by the performance of good experiments rather than the emergence of fundamental unifying ideas. Anderson and his colleagues at the California Institute of Technology, and Steinberger and his group at the University of California, have confirmed the earlier observations of Rochester and Butler, and there is now good evidence for an electrically neutral meson. Also, groups of investigators at the universities of Rochester and Minnesota have established the important role of heavy particles in cosmic ray events. The pioneering exploration of the nucleus just prior to and following the war is giving place to the careful quantitative experimentation necessary for the formulation of an adequate theory of nuclear phenomena. A start, but only a start, has been made on the careful measurement of the energetics of nuclear processes. The current theories of nuclei are heuristic and phenomenological, and the firm establishment of a general theory must apparently await the accumulation of more reliable and quantitative data.

War-born techniques have contributed to some of the most interesting recent experimental advances in atomic physics. Facility in the generation and measurement of radiation in the microwave region in the hands of many groups throughout the country is leading to the precise determination of the small energy intervals characterizing hyperfine structure in atomic and molecular spectra. This new technique is comparable in power to the development of the ruled grating by Rowland, and it leads directly to the precise measurement of magnetic dipole and electric quadrupole moments of nuclei. Precision measurements of the precessional frequency of the proton moment in known magnetic fields by Hippel and his colleagues at the National Bureau of Standards have not only yielded an absolute value of the ratio of the magnetic moment to the angular momentum of this elementary nuclear particle, but have provided a

simple and valuable general technique for determining magnetic field strengths in terms of frequencies. Extensions of such experiments to the measurement of characteristic rotational frequencies of ions in known magnetic fields by Hippel and also by Goudsmit and Smith at the Brookhaven National Laboratory promise to yield considerably more precise values than we have at present for atomic masses.

Finally, these techniques of precision frequency measurement in the microwave region by Hanson and Bolt at Stanford have led to a more accurate measurement of the velocity of light than we possessed heretofore. This is a fundamental parameter in atomic theory and an essential copulative datum between high-energy radiation, which is measured fundamentally in terms of a length, and low-energy radiation measured in terms of a frequency or time. It is interesting to note that the value obtained for the velocity of light by Michelson and his assistants over two decades ago was recently called into question by certain geodetic measurements of Aslakson, and the program started by Hanson for measuring the resonant frequency of a cavity with a precisely known dimension has corrected the value of this quantity, as well as extending the precision of the measurement.

The applications of physical techniques have stimulated other fields of science. The most striking recent instance is without doubt the use of the techniques of radioactivity in conjunction with artificially prepared radioactive substances in chemistry, biology, medicine, and archaeology. Tracer techniques furnish a method of attack upon the problems of organic materials and the processes of living organisms. These problems are of such magnitude and complexity as to appall the mere physicist, and he can but proffer this method in all humility to those courageous investigators who are undertaking to unravel the mysteries of a living cell.

G. P. HARNWELL

Randal Morgan Laboratory of Physics  
University of Pennsylvania

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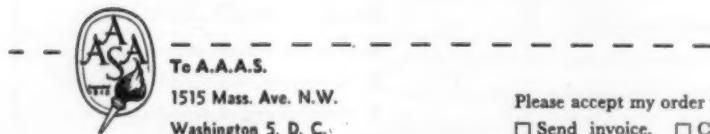
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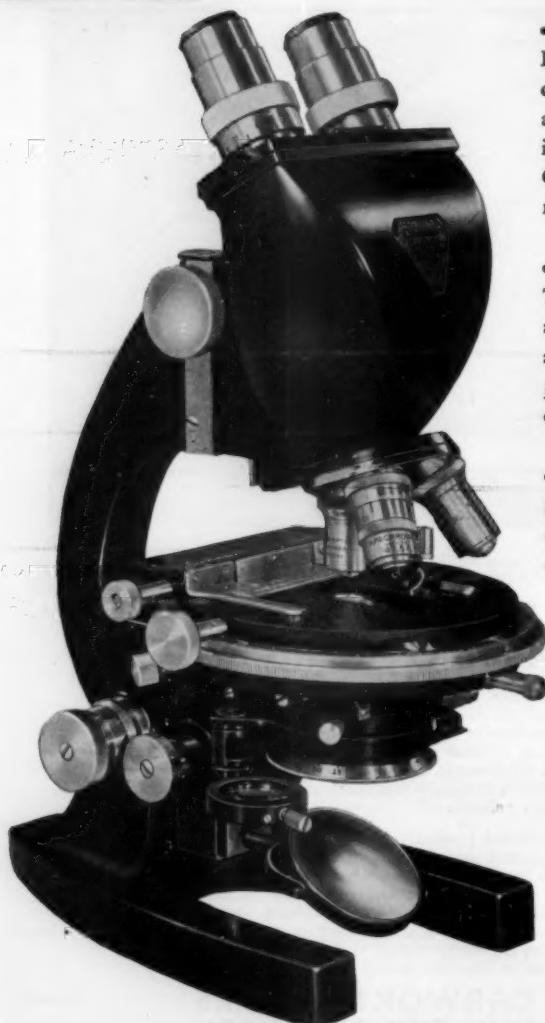
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# Max Planck, the Man and His Work<sup>1</sup>

Walter Meissner

Laboratory of Physics

Bavarian State Experiment Station of Technology, Munich, Germany

WHENEVER I THINK OF MAX PLANCK, my venerated teacher, with whom I took my doctorate in theoretical physics and with whom I was connected for thirty years in Berlin, I have an exalted and solemn feeling. I think of him, as the whole world of physicists does, as the creator of the world-shaking quantum theory; but for me he is even more—all that is one with truth, and hence with justice. He was never swayed by the opinion of others, not only in science but also in human relations, because he followed the path which he thought was the only true and good one. And this he did, not intolerantly, but in his own most modest manner. Never did he wish to appear more than he was. And this enhanced his commanding and gracious personality.

Planck's manner was determined to a certain extent by his education and the circle in which he grew up. He came from a family of jurists. He was born April 23, 1858, in Kiel, the sixth child of Wilhelm Planck, professor of law, and of his wife Emma (nee Patzig.) In his ninth year he moved to Munich, where his father had been offered a professorship at the university. The physicist Planck inherited the correct juridical way of his family in the administration of any position; for instance, as permanent secretary of the Prussian Academy of Science, he insisted upon the strictest objectivity and exact adherence to rules or decisions. He directed meetings in correct parliamentary manner, and always in his own charming and gracious way.

For a correct picture of Planck's personality, one must consider his training and his work. In Munich, Planck was a pupil in the famous Maximilian Gymnasium where, at the age of seventeen, he passed the university entrance examination. At first he was uncertain whether to select classical philology, music, or physics, but he finally decided on physics, in spite of the fact that Jolly, then professor of physics at the University of Munich, advised him against it, since in the field of physics there was nothing new to be discovered. Music remained for him a source of delight and recreation for the rest of his life.

Planck's decision to study physics may be attributed primarily to his mathematics teacher at the gymnasium, Herman Mueller, to whom he owed much, and through whom he became acquainted with the

principle of the conservation of energy, which later became the subject of a prize essay for the Goettingen Academy. Planck studied in Munich from 1875 till 1877. There he was far more attracted by the mathematician Bauer than by the physicist Jolly. It was Bauer who stimulated Planck's enthusiasm for higher mathematics and its unique methods of reasoning.

From 1877 to 1879, Planck continued his studies in Berlin. There his scientific horizon was considerably broadened by attending the lectures of Helmholtz, Kirchhoff, and Weierstrass; and the pioneering work of these research men was readily accessible to him. However, the lectures of Helmholtz were not, as Planck wrote later, of any particular advantage to him. With the exception of three (including Planck) the students finally stayed away. In Planck's words, "We had the feeling that in these lectures, Helmholtz was at least as bored as we were." Here was another example of a genius who is not necessarily a good teacher! Planck had similar experiences with Kirchhoff. "His lectures," says Planck, "gave the impression of being learned by heart; they were dry and monotonous. Nobody dared to doubt anything. As a consequence we did not learn very much, because one only learns by asking questions." Under these circumstances Planck was able to fulfill his desire for scientific knowledge only by reading on subjects of interest to him, and these happened to be subjects connected with the energy principle. He found the papers of Rudolph Clausius, written in lucid, understandable language. He said later that their illuminating clarity impressed him so tremendously that he became enthusiastically absorbed in their serious study.

Planck particularly appreciated Clausius' precise formulation of the two laws of thermodynamics and the clear distinction between the two. Up to then, as a consequence of the theory of heat as a substance, it was assumed that the transition of heat from a higher to a lower temperature was similar to the falling of a weight from a higher to a lower position. This erroneous idea was not to be displaced easily. Clausius, on the other hand, according to Planck, derived his proof of the second law from the hypothesis that "heat cannot pass spontaneously from a colder to a warmer body." This hypothesis, however, requires clarification. It not only expresses the idea that heat does not go directly from a colder to a warmer material, but also indicates that in no way is it possible to transmit heat from a colder to a warmer material without "some other change remaining in nature as a compensation." While trying to clarify this point,

<sup>1</sup> Translated from the German by members of the Department of Physics, Purdue University. Based in part on Max Planck's *Wissenschaftliche Selbstbiographie*, Leipzig: Johann Ambrosius Barth (1948); English trans., New York: Philosophical Library (1949). See also MEISSNER, W. *Ber. Bayer. Akad. Wiss.*, 1 (1948).

Planck found a formulation of the hypothesis that seemed simpler and more convenient: namely, the process of heat conduction cannot be completely reversed by any means; or, the expansion of a gas without the performance of work cannot in any fashion be made completely reversible—a concept that is the same as that of Clausius, yet not requiring a special explanation. Planck calls a process "natural" which cannot be made reversible. Today we call it "irreversible." "To this very day," Planck wrote later, "I find, instead of the above definition of irreversibility, the following: 'A process is irreversible if it cannot take place in the opposite direction.' This definition is not sufficient. Because, at the outset, it is quite conceivable that a process that cannot take place in an opposite direction could become somehow completely reversed." In an irreversible process nature has a great "preference" for the final state. A measure of this "preference" is Clausius' entropy. The meaning of the second law of thermodynamics is, then, an increase in the sum of the entropies of all bodies participating in the process.

Planck finished his doctor's thesis in 1879 without the assistance of his teachers. He presented it after his return to Munich and received his degree in the same year. Very much to his disappointment Planck found that his thesis had made no impression whatsoever on the contemporary world of physics. His Munich professors just let it pass. Adolf von Bayer, the famous chemist, let it be understood that he thought theoretical physics superfluous. Helmholtz very likely never read the paper. Kirchhoff definitely disapproved, with the remark that the concept of entropy, which is only measurable through a reversible process and hence can only be thus defined, cannot be applied to irreversible processes. It was impossible to approach Clausius, who did not answer letters; nor did an attempt to introduce himself personally in Bonn have any result, because Clausius was not at home. Correspondence with Carl Neumann, in Leipzig, had no result whatever.

Planck had a similar experience in Munich (1880) with his habilitation paper, "States of Equilibria of Isotropic Bodies." He made use of the general results of his Ph.D. thesis for the solution of a number of concrete thermodynamic (particularly physicochemical) processes, but this work likewise made no impression on the physicists of his day.

These rather disheartening experiences did not prevent Planck, convinced of the importance of the task at hand, from continuing the study of entropy. It is characteristic of his sure intuition and superior scientific insight, as well as of his happy disposition, that lack of recognition did not discourage him; far from it, he continued in the direction in which he had started, and this enabled him to develop the quantum theory, his greatest achievement. The next problem that Planck attacked was the thermodynamic equilibrium of gaseous mixtures, whereby he made use, for the first time, of Helmholtz' "free energy."

Stimulated by the desire "to become somehow favorably known in the scientific world" and to receive a professorship, Planck decided to work on the prize problem set by the Goettingen philosophical faculty for the year 1887 concerning the nature of energy. It is true, he received only second prize—undoubtedly because, in a controversy between Wilhelm Weber, professor of physics in Goettingen, and Helmholtz, Planck with his usual sincerity definitely took Helmholtz' side. In judging the paper the faculty disagreed with his remarks. Even now it is a pleasure to read his clear and comprehensive treatise, in which the results of Mayer, Joule, and Helmholtz are discussed in detail, and in which Planck gave some ideas of his own.

Before this work was finished, Planck received a call as professor extraordinary of theoretical physics at the University of Kiel (spring of 1885). "This offer," so Planck writes, "came to me as a redemption. I consider one of the happiest occasions of my life the moment when Ministerial Director Althoff . . . informed me about the conditions of my appointment."

During this stay in Kiel, from 1885 to 1889, Planck again worked on his favorite theme and wrote a number of essays under the title "The Principle of the Increase of Entropy." In these articles he dealt with heterogeneous equilibria (the equilibria between various states of aggregation), the mass law of action for gases, and the derivation of the thermodynamic functions for dilute solutions (particularly the entropy). His results went far beyond those of Van't Hoff. The activity coefficient, which enters into Van't Hoff's treatment of the boiling point elevation, must have the value 1, as Planck showed from the second law of thermodynamics. A deviation from the value 1 would be possible only if the dissolved molecules were dissociated. In 1943, in his paper on the history of the discovery of the elementary quantum of action, he states that some of his results, in their fruitful applications, were anticipated by the great American physicist J. W. Gibbs; nevertheless, one must admit that certain results of Planck's were truly pioneering.

It is also important to note that, even then, Planck was sure of himself as regards the objections of others. Particularly with respect to the remarks of the Swedish physical chemist Svante Arrhenius, he was able to defend himself and to prove clearly that the use of ideal processes is permissible. In this connection he also points to the use of ideal semipermeable membranes by Gibbs and Van't Hoff:

In view of this undoubtedly success, one must admit that these ideal processes are a most useful research tool, and one must expect that, if properly used, they will in the future lead to new results. Indeed, I would say that they are a particular triumph of the human mind, which, with their help, has been able to discover the correlation between laws of nature in fields that are entirely closed to direct experiments.

In the spring of 1889, after the death of Kirchhoff,

Planck, at thirty, was called to the University of Berlin as his successor. Undoubtedly he had been recommended by Helmholtz, who had been particularly impressed by Planck's prize essay on the energy principle, who had appreciated his exceptional qualifications, and who had known him personally at an earlier time. In Berlin he had the great fortune to become intimate with Werner von Siemens, and particularly with Helmholtz. Of this we shall speak later.

In science Planck continued his thermodynamics work until 1896. After a few minor papers, he published the fourth part of his great work on the principle of the increase of entropy, which presented the theories of thermoelectricity and of the electrolytic concentration cell (1891). Clausius had worked from 1867 until his death editing his collected papers on the mechanical theory of heat, but was unable to finish. After Clausius' death in 1888, Planck and K. Pölfriech edited the third volume of Clausius' treatise, in which the kinetic theory of gases was discussed. This volume appeared in 1894. Planck also edited Volume III of Kirchhoff's lectures on electricity and magnetism (theoretical physics).

In 1892 Planck was promoted to full professor. In 1893 he published an outline of general thermochemistry. In the same year, in the Physical Society of Berlin, he delivered a memorial address on Heinrich Hertz, which was greatly appreciated by Helmholtz. In 1894, Planck was elected to the Prussian Academy of Science, in which he served from 1912-1938 as permanent secretary of the mathematical-physical science section.

Of his many shorter papers mention should be made of a publication on the proof of the Maxwell distribution law (1896) in the proceedings of the Bavarian Academy of Science. A remark on a demonstration of a new type of harmonium in the "true" natural scale (system of C. Eitz) appeared in the proceedings of the Physical Society of Berlin in 1893. Planck, with his outstanding musical talent, had a particular interest in this harmonium (as will be discussed later).

In 1897 the first edition of his lectures on thermodynamics appeared, to be followed later by the publication of some of his other lectures. His election to the Academy and his contacts in the Physical Society gave him the impetus to work on heat radiation and to develop his theory of radiation, which later won him the Nobel prize. What he had particularly in mind in this paper was the interrelation of electrodynamics with thermodynamics. He had come to the conclusion that in every physical process the behavior of entropy has to be considered, and that this must also hold for the theory of radiation. Again he used ideal processes, which he had already justified in detail in his thermodynamics.

Following Kirchhoff's radiation law, he considered an evacuated cavity, bounded by totally reflecting walls, in which are located linear electrical oscillators of definite characteristic frequency and with weak

radiation damping. He believed that, through irreversible radiation processes, the black-body radiation, even assuming arbitrary starting conditions and applying Maxwell's theory, would lead to a stationary state—thermodynamic equilibrium. Boltzmann pointed out, however, that this approach is erroneous, hence a new principle had to be added to reach the final goal. This was the hypothesis of "natural radiation," according to which the various partial vibrations of the heat radiation waves are entirely incoherent. Only with this hypothesis can radiation processes be considered irreversible so that thermodynamic equilibrium is reached. On the basis of this irreversibility, Planck was able to find an expression for the entropy of the oscillator, as well as of the black-body radiation itself. In thermodynamic equilibrium this entropy has a maximum, and the corresponding final state depends only on the absolute temperature. The entropy is a function of energy and of frequency, the form of which (introduced by Planck) contains a certain arbitrariness. With this first assumption for the entropy Planck derived Wien's law (1896) for the energy distribution in black-body radiation. In any event, he recognized then that the dependence of entropy on the energy and the frequency has a fundamental importance for the investigation of heat radiation. His assumption for the value of the entropy had to be discarded when it was found that Wien's radiation law was not generally confirmed by measurements. O. Lummer, E. Pringsheim, and, later, F. Paschen pointed out deviations in the range of long wavelengths.

A decisive change was brought about when F. Kurlbaum presented the results of energy measurements for very long wavelengths (carried out with H. Rubens) in a session of the German Physical Society (October 19, 1900). These measurements indicate that, with increasing temperature, the intensity of the black-body radiation approaches proportionality to the absolute temperature  $T$ , corresponding to Rayleigh's radiation law (1900). This, however, contradicts Wien's radiation law, according to which the intensity of radiation must always remain finite. In view of these results, communicated to him a few days before the session of the Physical Society, Planck started looking for a way out of the difficulty, and found at first an empirical solution. According to Rayleigh's radiation law, since the energy  $U$  of the Planck oscillator at a fixed frequency is always proportional to the intensity of radiation (Rayleigh's radiation law) if  $T$  is the absolute temperature,  $U = CT$ . With the thermodynamic relation for the en-

tropy at constant volume,  $\frac{dS}{dU} = \frac{1}{T}$ , one has  $\frac{d^2S}{dU^2} = -\frac{C}{U^2}$ .

To Planck's first assumption for the entropy and Wien's law corresponds the value  $d^2S/dU^2 = -1/\alpha v U$ , where  $v$  is frequency per second. Planck now set up an interpolation formula for the two values of  $d^2S/dU^2$ , setting  $d^2S/dU^2 = -1/(\alpha v U + U^2/C)$ . This

interpolation formula, together with the expression for  $dS/dU = 1/T$ , leads immediately to the Planck radiation law:  $I_v = Uv^2/c^3 = C_1 v^3/(e^{C_2/vT} - 1)$ , where  $c$  is the light velocity. He finished his calculations in time to communicate the results at the Physical Society session of October 1900. I myself have seen a postcard from Planck to Rubens communicating his radiation law even before this session. The law had already been confirmed by Kurlbaum and Rubens, and by Lummer and Pringsheim, and the agreement became even better with more precise measurements.

Within the next two weeks, Planck was able to derive the empirical interpolation formula from theory.<sup>2</sup> The salient point was to find an unambiguous way to calculate the dependence of entropy on energy and frequency. He realized that this was impossible by means of electrodynamics alone, so he used Boltzmann's method and set the entropy proportional to the logarithm of probability. Only through the introduction of energy quanta was he able, with the aid of probability calculations, to obtain his interpolation formula. The energy quantum was set equal to the product of the frequency and a new constant  $\hbar$ —Planck's elementary quantum of action. From the experimental values of the radiation constants, he was able, not only to calculate the numerical value of the elementary quantum of action, but also to determine the proportionality factor  $k$  in the Boltzmann expression for entropy, as well as the value of  $e$ , the charge of the elementary quantum of electricity. The following values resulted:

$$k = 1.346 \times 10^{-16} \text{ erg}/^\circ\text{K}; \quad \hbar = 6.55 \times 10^{-27} \text{ erg-sec}; \\ e = 4.69 \times 10^{-10} \text{ esu}.$$

Planck's radiation law then took the form  $I_v = Uv^2/c^3 = hv^3/c^3(e^{hv/kT} - 1)$ , so that the constants  $C_1$  and  $C_2$  are now universally determined. Today the best values for the constants  $k$ ,  $\hbar$ , and  $e$  are the following:  $k = 1.380 \times 10^{-16} \text{ erg}/^\circ\text{K}$ ;  $\hbar = 6.626 \times 10^{-27} \text{ erg-sec}$ ;  $e = 4.803 \times 10^{-10} \text{ esu}$ . Planck's calculated values of 1900 were surprisingly good! The constant  $k$ , which Boltzmann had never really used, was calculated by Planck for the first time (as Planck has pointed out several times—e.g., in his Nobel prize address). It should really not be called Boltzmann's constant, but rather the Boltzmann-Planck constant. The calculation of the elementary quantum of electricity  $e$  from radiation measurements was not taken very seriously by many, in spite of the fact that in 1900 it was by far the most accurate determination. This was first demonstrated by the measurements of H. Geiger and E. Rutherford in 1908. As Rutherford said later, Planck's calculation made an overwhelming impression.

In his first derivation of the radiation law, Planck had assumed quantization of both emission through oscillators, as well as absorption through resonators. This is the presentation in Planck's lectures during the winter semester of 1905–06 on the theory of heat

<sup>2</sup>The theory was finally communicated to the Prussian Academy on December 14, 1900, in "The Birthday of the Quantum Theory" (Laue).

radiation (published in 1906). For some time Planck assumed, instead of absorption in quanta, a continuous absorption. But this derivation was not particularly satisfying. I still remember how Nernst, in the session of the Physical Society in Berlin, when Planck discussed this new derivation, at once contradicted it and spoke of something similar to Einstein's photons, so that Planck left the session somewhat depressed. At first, however, he persisted in this new derivation.

The reason for all the difficulties was quite profound. It is to be found in the dual nature of the quantum of radiation which behaves, depending on circumstances, sometimes like a particle and sometimes like a wave. It is known that Einstein first introduced with striking success the hypothesis that not only emission takes place in quanta, but that also heat and light rays are propagated as quanta—photons. But already Einstein's derivation of Planck's law, considering photons in a cavity, involves the dual nature of the photons: the photons were ascribed a certain frequency. The dual nature of the photons is displayed particularly in the energy fluctuations of heat radiation (Einstein). They are composed of one term proportional to the quantum of energy, and an average energy (quantum term); but there is a second term that is proportional to the square of the average energy (classical interference term; Lorentz). Planck has also treated this fluctuation law of Einstein's in some detail.

He continued to discuss other questions in this field. In this connection, we particularly want to mention that, in a communication to the Franklin Institute in 1927, Planck, considering the development of the quantum theory through De Broglie, Heisenberg, Born, Jordan, Schrödinger, and others, says:

The classical theory recognizes and treats only the two extreme cases; on the one side, corpuscular motions, on whose outermost border lies the uniform motion of a particle in a straight line; on the other side, wave-motions, on whose outer limit lies the static, homogeneous field. Looked upon from the newly established point of view, there is neither pure corpuscular motion, nor any pure wave-motion. Rather, every corpuscular motion includes something of wave-motion, and every wave-motion something of corpuscular motion. The difference is only gradual and quantitative. In the motion of a particle, as soon as the ratio of the impulse to the curvature of the path, which in motion in a straight line has an infinite value, sinks to the order of magnitude of the universal constant of action, the laws of wave-motion begin to play an appreciable part. And vice versa, in monochromatic light, as soon as the ratio of its energy to its frequency, which is infinite in a static field, sinks to the order of magnitude just mentioned, the corpuscular laws begin to be appreciable. In what relation, however, the corpuscular laws stand to the laws of wave-motion in the general case, remains the great problem, to which at the present time a whole generation of investigators is devoting its best efforts (*J. Franklin Inst.*, 204, 18 [1927]).

This synthesis Planck has attempted in papers appearing in the *Annalen der Physik* (1940, 1941). Some of his results had already been published in earlier papers by Kramers. The changed action function is new and also the change in the boundary conditions of wave mechanics.

If one asks for the most logical derivation of Planck's radiation law available today, the one least open to objections, one could say the following: Quantum mechanics has shown that, for identical particles, only Bose-Einstein or Fermi-Dirac statistics can be used (the latter only if the Pauli principle has to be used). To derive the radiation law free from classical electrodynamics, which is incompatible with quantum theory, then, with Bose, one reasons as follows: (1) The radiation consists of light quanta of energy  $h\nu$ , and a momentum corresponding to the relativistic relation between energy and mass. (2) The phase volume (position coordinates and momenta) for light quanta consists of cells of magnitude  $\hbar^3$ . (3) The definition of entropy as  $k$  times the logarithm of the thermodynamic probability, and Bose-Einstein statistics applied to radiation in thermodynamic equilibrium (in a given volume with a given total energy), lead without any other assumption to Planck's radiation law. We postulate now what Planck had to deduce from his derivation of the radiation law. This postulate has been proved through innumerable experiments, so that now one is justified in taking this as a given fact in starting calculations.

The classical theory was at a deadlock, and only a genius such as Planck's could overcome the formalistic difficulties by assuming intuitively the only possible way out, the existence of discrete energy quanta of magnitude  $h\nu$ . Nowadays this must be considered as fundamental a law, and probably just as reliable, as the law of the conservation of energy or the law of entropy. Whereas the number and kind of elementary particles are increasing all the time, there remains only one elementary quantum of action, Planck's  $h$ .

The riddle of the dual nature of particle and light quantum is not solved through Bose's derivation of Planck's law; it is simply introduced as a fact. Also the questions whether the principle of causality fails in the realm of quantum theory, and whether Heisenberg's uncertainty relation, which follows logically if one uses Newtonian point mechanics, is the last word of wisdom, are not even touched. Planck himself considered the complete clarification of these questions as a goal still to be reached. Thus in the last sentence of an essay in *Naturwissenschaften* (1943) he says, "I am furthermore convinced that we will need still more profound, at the present time not even clearly predictable, changes in our physical concepts before the quantum theory will have the degree of perfection that used to be ascribed to the classical theory."

We must remember that Planck actively supported Einstein's special theory of relativity. In a detailed paper in the *Annalen*, he gave the relativistic treatment of the dynamics of moving systems. It was Planck and Nernst who were responsible for Einstein's call to Berlin. I know from personal experience that Planck was at first skeptical about the general theory of relativity, but was unable to resist the great ideas of this theory very long.

What we have said so far, in considering the sci-

entific development and the investigations of Planck, reveals many characteristic traits of his personality: his entirely independent way of thinking, his tremendous superiority to most of his contemporaries, and his happy disposition, which was not deterred by the lack of appreciation he at first encountered. But to get a better picture of his personality we should go into some details of his personal life and into the manifold activities that are not immediately connected with his scientific work.

Because of his great musical ability, Planck as a student came in contact with many art circles in Munich. He was frequently with the families of Paul Heyse, Piloty, Woelflin, Stieler, etc. He participated in theatricals and he wrote songs, short plays, and even an operetta. Planck had the gift of absolute pitch. In school he sang the soprano parts of the great oratorios in boys' choirs. As a student, he was second choirmaster in the academic singing society, and he played the organ at church. He systematically studied piano during his student years in Berlin, so that throughout his whole life he found a daily joy and relaxation in playing the piano. Returning to Munich, he studied harmony and counterpoint with Rheinberger. He particularly liked to play Schubert and Brahms.

Planck's call to Kiel meant not only scientific success but also personal happiness. While living with his parents, he had the most charming and comfortable life imaginable, but the desire to be independent became more and more pressing, and he was eager to have a home of his own. In 1887, at the age of not quite twenty-nine years, he married a friend of his youth, a daughter of the Munich banker Merek, Marie Merek, with whom he had two sons and two daughters. She died in 1909.

In Berlin, he first lived in the west end, but later he built a villa in the Gruenewald. On Planck's arrival in Berlin, von Siemens and Helmholtz were the spiritual leaders of the Berlin Physical Society. Planck during his Berlin student days did not appreciate Helmholtz' lectures, and Helmholtz in turn ignored Planck's Ph.D. thesis; however, as a colleague of Helmholtz, Planck soon became his great admirer. "In his personality," so Planck wrote later, "was embodied the dignity and truthfulness of his science." Every appreciative or commendatory word of Helmholtz gave Planck more satisfaction than any outside success. Throughout his whole life he treasured the appreciative words of Helmholtz after his memorial address on Heinrich Hertz in 1894. Planck participated many times in the social gatherings of the Helmholtz family, and he wrote of how memorable were the evenings spent at the Helmholtz' hearing Joseph Joachim play his own arrangements of the newly published Hungarian dances by Brahms, or Marianne Brand and the baritone Oberhauser singing "Wotan's Farewell" from *Die Walküre*.

After Helmholtz' death, Planck continued the musical tradition in his own home in the Gruenewald

colony. He played an hour every day and also conducted a choir of friends and students. When three of his fingers became stiff, he still spent some time every day at the piano and, as a physicist, derived particular pleasure from the harmonium with natural scale, a complicated instrument because of the large number of keys.

Music was not Planck's only source of recreation and relaxation. Every year, he spent several weeks in the mountains, where he undertook regular climbing tours. Even now, his name may be found in the registers on many mountaintops. At the age of seventy-two he climbed the Jungfrau, and at seventy-nine the Grossvenediger. At home he went regularly for walks. Since he himself had such a strong need for exercise, he very energetically recommended exercise for the students during the time when he was Rector at the University of Berlin (1913-14). In every respect, Planck's life was arranged in such a way that he never overworked; he was able, therefore, to make the most of his tremendous talent. For him, as only rarely for anyone else, the old saying is true: *In corpore sana mens sana*.

In order to devote the necessary amount of work to his research in physics, in spite of leading a carefully regulated life, wise limitations were necessary. This explains why Planck never had a large institute with many assistants and doctoral candidates. After holding his lectures and his recitations, he usually went home. Thus one may understand why Planck had only nine doctoral students altogether. As he had finished his own thesis entirely unassisted, he also expected from each Ph.D. candidate a large amount of self-reliance. As an example, Planck merely gave me the theme for my own dissertation without ever asking how the work was progressing; and when I delivered it after half a year, Planck accepted it without changing a single word and had it published. Those who took degrees with him were: M. Abraham (1897), M. v. Laue (1903), M. Schlick (1904), Von Mosengail (who shortly after his examination had a fatal accident in the Alps), and I myself (1906), Reiche (1907), Lamla and W. Schottky (1912), and W. Bothe (1914). The student who was closest to him, according to his own words, was Laue.

Obviously, not only his few doctoral candidates, but also the many who took his lectures and learned from his books must be considered as Planck's students. Altenkirch, a specialist in technical thermodynamics (recently a Linde medalist) is one of them. Planck's lectures, all of which I attended, were prepared to the smallest detail, and were of unsurpassed clarity. To hear them was an aesthetic pleasure. Of all the lectures I have ever heard, Planck's have made the deepest impression. As vivid as if it had been yesterday is the set of lectures given during the winter semester of 1905-06, when he lectured for the first time on the quantum theory and discussed the elementary quantum of action. It was almost as if he were embarrassed to talk about his own ideas, which it was

absolutely necessary to discuss with his own students. In his lectures and recitations his students were introduced to theoretical physics, and they learned to discuss all questions in a thorough, logically indisputable manner.

One activity in which Planck participated regularly and actively was the physics colloquium at the University of Berlin. It was an especially outstanding period when Nernst, Einstein, Laue, and, for a time, Schroedinger were in Berlin. The characteristic differences in their various points of view became particularly clear. Planck was always very cautious in his remarks. Laue was the very soul of the colloquia, and Einstein and Nernst had something to say on every subject, with an amazing presence of mind and without long deliberation. We had especially lively times when Ehrenfest, with his effervescent temperament, was a guest in the colloquium. Planck, however, always maintained his poise and dignity. In the thirties he was the great silent one in the colloquium. He attended the meetings faithfully without ever taking part in the discussion. This self-restraint was characteristic of his type of mind. He must have had the feeling that he no longer had enough presence of mind to discuss questions spontaneously, despite the fact that, up to his last year, he was able to think as logically and sharply as anyone else if he had the time and leisure to do so.

Planck's dignity and graciousness manifested themselves in the administration of the various positions he held at different times in Berlin. From 1912 to 1938 he was permanent secretary of the mathematical-physics section of the Prussian Academy of Science. His many addresses and responses to the addresses of others were characteristic of his personality. In his own inaugural address he stressed the need to turn away from the idea that all physical phenomena can be reduced to mechanical processes, the fundamental significance of the two laws of thermodynamics, the summary of experimental results through theoretical physics, which is necessary to stimulate further experiment.

In his response to Einstein's inaugural address he did not refrain from being critical. "Even if you are not satisfied with the principle of relativity in its first special form because it favors uniform motion, one should recognize this as a particular advance in knowledge; because the laws of nature which we are looking for are a special selection from the manifold possibilities of all possible relations."

Later, however, he was not able to deny the great importance of the general theory of relativity. In response to Laue's inaugural Planck discussed qualities of leadership for a position such as Laue already held: "Conscientiousness in the pursuit of important things, patience, and the courage to stand up for his own convictions against anybody, even against his own former and different opinion." In a similar way every address he gave in the academy was always illuminated by his profound and mature personality.

With this same thoroughness and from the same point of view as he fulfilled his duties as permanent secretary in the academy, Planck also took the position of president of the Kaiser Wilhelm Society (1920-37) in difficult times, when national socialism displayed its corrupt power. The greatest disappointment in this position was perhaps his interview with Hitler in an attempt to retain the Jewish associates of the Kaiser Wilhelm Institute. The interview had no practical results, and this may have been the reason for the disastrous end of his favorite son. His presidential post, however, gave Planck the opportunity to venture beyond his special professional duties—a welcome opportunity for his broad interests, which also encompassed philosophical and religious problems.

This attitude is shown in all Planck's scientific work. He himself says in his essays in *Naturwissenschaften* (1943), "Of primary interest to me in physics were all the great general laws, which are significant for all processes in nature independent of the properties of the bodies involved in the process, and independent of the idea which one has about their structure. For this reason the two laws of thermodynamics are of particular interest for me." How far his interest went beyond physics is easily seen by looking at his lectures and essays in his later years. They deal with the idea of causality in physics, with determinism and indeterminism, with the meaning and limits of exact science, with religion and science, with phantom problems about which he lectured in Goettingen in 1946. Let us quote from the essay on the meaning and limits of exact science just one sentence, which is particularly characteristic of Plank's thinking: "The only thing which we can claim with certainty as our property, the greatest good which no power in the world can rob us of, and which can make us happy forever as nothing else can, is a pure spirit, which finds its expression in the conscientious fulfilling of one's duties." Even if Planck's collection of philosophic writings—e.g., his lecture on phantom problems—did not find general approval, in all of them we see the burning wish to obtain honest clarity about the most profound problems of human life.

The greatness and strength of his character Planck showed particularly in the way he carried his personal burdens: The four children by his first wife all died. His twin daughters both died in childbirth. The oldest son was killed in the first world war near Thiaumont in France. The second son came to a frightful end in January 1943 as a victim of Nazism. When Planck heard of it, he wrote to Sommerfeld that he had lost his closest and best friend. He was wrestling for the power to give his future life meaning by conscientious work.

In his personal misfortunes he was comforted by his second wife (nee Hoesslin), the niece of his first wife, whom he married one year after the latter's death.

The second world war destroyed Planck's beloved home in the Gruenewald, with all his possessions, including his carefully kept diary. He and his wife were forced to flee to his estate of Rogätz on the Elbe. He almost died in an air raid on Kassel. From Rogätz the Americans took him to Goettingen, where he found refuge with some kinfolk and where he spent his last two and a half years. He died in the hospital on October 4, 1947, about half a year before he would have celebrated his ninetieth birthday.

Planck's second wife, Marga, was up to the last hour a self-sacrificing help to him. On all his mountain trips she was a faithful companion, and in his home and in his life she provided all the graciousness that he desired. Without her his life would have been extremely difficult. She survived him by one year.

Many honors came to Planck in the course of his life, and they may have compensated for the fact that in the beginning he found no recognition at all. He was a member of all German and of many foreign academies. As a member of the Royal Society of London, he participated in the Newtonian celebration held in London the year before his death. A great many scientific societies made him an honorary member. He was many times an honorary doctor (e.g., Cambridge). He also was awarded the Lorentz medal, the Order Pour le Mérite (*Friedensklasse*), of which later he became Chancellor; and perhaps the greatest recognition, the Nobel prize for his radiation law (1919). Besides his trip to London in 1946, Planck accepted many invitations to foreign countries (America, France, England, and Switzerland). He was a regular participant in the Solvay Congresses in Belgium.

His sixtieth birthday was celebrated by the German Physical Society in Berlin. Addresses were given by Warburg, Laue, Sommerfeld, and Einstein. His seventieth birthday was celebrated in his home and by the Physical Society of Berlin. Particularly imposing was the celebration of his eightieth birthday in the Harnack-Haus in Berlin, in which Ramsauer, Grueneisen, Debye, Laue, and the French Ambassador, François Poncet, gave addresses. The beautiful gold medal Planck awarded to Léon de Broglie was accepted for him by the French Ambassador. On the evening of Planck's eightieth birthday there were addresses by Sommerfeld, by Fokker for the Dutch physicists, and by Kopff for the astronomers. Planck found simple dignified words of thanks on these occasions.

Planck will go down in history as one of the immortals, the man who had the courage to break with classical physics and to introduce the elementary quantum of action. In the hearts of all who were close to him he will remain to their own last hour a pure, simple, and noble character whom they recall with deep veneration and love.

# The Advent of the Quantum Theory<sup>1</sup>

Albert Einstein

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THE REVOLUTION [in classical physics] begun by the introduction of the field was by no means finished. Then it happened that, around the turn of the century, independently of what we have just been discussing,<sup>2</sup> a second fundamental crisis set in, the seriousness of which was suddenly recognized due to Max Planck's investigations into heat radiation (1900). The history of this event is all the more remarkable because, at least in its first phase, it was not in any way influenced by any surprising discoveries of an experimental nature.

On thermodynamic grounds Kirchhoff had concluded that the energy density and the spectral composition of radiation in a *Hohlraum*, surrounded by impenetrable walls of the temperature  $T$ , would be independent of the nature of the walls. That is to say, the nonchromatic density of radiation  $\rho$  is a universal function of the frequency  $\nu$  and of the absolute temperature  $T$ . Thus arose the interesting problem of determining this function  $\rho(\nu, T)$ . What could theoretically be ascertained about this function? According to Maxwell's theory, the radiation had to exert a pressure on the walls, determined by the total energy density. From this Boltzmann concluded, by means of pure thermodynamics, that the entire energy density of the radiation ( $\int \rho d\nu$ ) is proportional to  $T^4$ . In this way he found a theoretical justification of a law which had previously been discovered empirically by Stefan, i.e., in this way he connected this empirical law with the basis of Maxwell's theory. Thereafter, by way of an ingenious thermodynamic consideration, which also made use of Maxwell's theory, W. Wien found that the universal function  $\rho$  of the two variables  $\nu$  and  $T$  would have to be of the form

$$\rho \approx \nu^3 f\left(\frac{\nu}{T}\right) \text{ whereby } f(\nu/T) \text{ is a universal function}$$

of one variable  $\nu/T$  only. It was clear that the theoretical determination of this universal function  $f$  was of fundamental importance—this was precisely the task which confronted Planck. Careful measurements had led to a very precise empirical determination of the function  $f$ . Relying on those empirical measurements, he succeeded in the first place in finding a statement which rendered the measurements very well indeed:

<sup>1</sup> SCHILPP, P. A., Ed. *Albert Einstein: Philosopher-Scientist*. The Library of Living Philosophers, Vol. VII, 37–51 (1949). New York: Tudor Pub. (distributors). Excerpt reprinted by permission of the author, publisher, and distributor. Copyright by The Library of Living Philosophers, Evanston, Ill.

<sup>2</sup> In the preceding pages Einstein discusses the field theory and the changes it wrought in the conceptions of classical physics.

$$\rho = \frac{8\pi h\nu^3}{c^3} \frac{1}{\exp(h\nu/kT) - 1}$$

whereby  $h$  and  $k$  are two universal constants, the first of which led to quantum theory. Because of the denominator, this formula looks a bit queer. Was it possible to derive it theoretically? Planck actually did find a derivation, the imperfections of which remained at first hidden, which latter fact was most fortunate for the development of physics. If this formula was correct, it permitted, with the aid of Maxwell's theory, the calculation of the average energy  $E$  of a quasimonochromatic oscillator within the field of radiation:

$$E = \frac{h\nu}{\exp(h\nu/kT) - 1}$$

Planck preferred to attempt calculating this latter magnitude theoretically. In this effort, thermodynamics, for the time being, proved no longer helpful, and neither did Maxwell's theory. The following circumstance was unusually encouraging in this formula. For high temperatures (with a fixed  $\nu$ ) it yielded the expression  $E = kT$ . This is the same expression as the kinetic theory of gases yields for the average energy of a mass-point which is capable of oscillating elastically in one dimension. For in kinetic gas theory one gets  $E = (R/N)T$ , whereby  $R$  means the constant of the equation of state of a gas, and  $N$  the number of molecules per mol, from which constant one can compute the absolute size of the atom. Putting these two expressions equal to each other one gets  $N = R/k$ . The one constant of Planck's formula consequently furnishes exactly the correct size of the atom. The numerical value agreed satisfactorily with the determinations of  $N$  by means of kinetic gas theory, even though these latter were not very accurate.

This was a great success, which Planck clearly recognized. But the matter has a serious drawback, which Planck fortunately overlooked at first. For the same considerations demand in fact that the relation  $E = kT$  would also have to be valid for low temperatures. In that case, however, it would be all over with Planck's formula and with the constant  $h$ . From the existing theory, therefore, the correct conclusion would have been: the average kinetic energy of the oscillator is either given incorrectly by the theory of gases, which would imply a refutation of (statistical) mechanics; or else the average energy of the oscillator follows incorrectly from Maxwell's theory, which would imply a refutation of the latter. Under such circumstances it is most probable that both theories are correct only at the limits, but are otherwise false; this is indeed the situation, as we shall see in what

follows. If Planck had drawn this conclusion, he probably would not have made his great discovery, because the foundation would have been withdrawn from pure deductive reasoning.

Now back to Planck's reasoning. On the basis of the kinetic theory of gases Boltzmann had discovered that, aside from a constant factor, entropy is equivalent to the logarithm of the "probability" of the state under consideration. Through this insight he recognized the nature of courses of events which, in the sense of thermodynamics, are "irreversible." Seen from the molecular-mechanical point of view, however, all courses of events are reversible. If one calls a molecular-theoretically defined state a microscopically described one, or, more briefly, micro-state, and a state described in terms of thermodynamics a macro-state, then an immensely large number ( $Z$ ) of states belong to a macroscopic condition.  $Z$  then is a measure of the probability of a chosen macro-state. This idea appears to be of outstanding importance also because of the fact that its usefulness is not limited to microscopic description on the basis of mechanics. Planck recognized this and applied the Boltzmann principle to a system which consists of very many resonators of the same frequency  $\nu$ . The macroscopic situation is given through the total energy of the oscillation of all resonators, a micro-condition through determination of the (instantaneous) energy of each individual resonator. In order then to be able to express the number of the micro-states belonging to a macro-state by means of a finite number, he (Planck) divided the total energy into a large but finite number of identical energy-elements  $\epsilon$  and asked: In how many ways can these energy-elements be divided among the resonators? The logarithm of this number, then, furnishes the entropy and thus (via thermodynamics) the temperature of the system. Planck got his radiation-formula if he chose his energy-elements  $\epsilon$  of the magnitude  $\epsilon = h\nu$ . The decisive element in doing this lies in the fact that the result depends on taking for  $\epsilon$  a definite finite value, i.e., that one does not go to the limit  $\epsilon = 0$ . This form of reasoning does not make obvious the fact that it contradicts the mechanical and electrodynamic basis, upon which the derivation otherwise depends. Actually, however, the derivation presupposes implicitly that energy can be absorbed and emitted by the individual resonator only in "quanta" of magnitude  $h\nu$ , i.e., that the energy of a mechanical structure capable of oscillations, as well as the energy of radiation, can be transferred only in such quanta—in contradiction to the laws of mechanics and electrodynamics. The contradiction with dynamics was here fundamental; whereas the contradiction with electrodynamics could be less fundamental. For the expression for the density of radiation-energy, although it is compatible with Maxwell's equations, is not a necessary consequence of these equations. That this expression furnishes important average-values is shown by the fact that the Stefan-Boltzmann law and

Wien's law, which are based on it, are in agreement with experience.

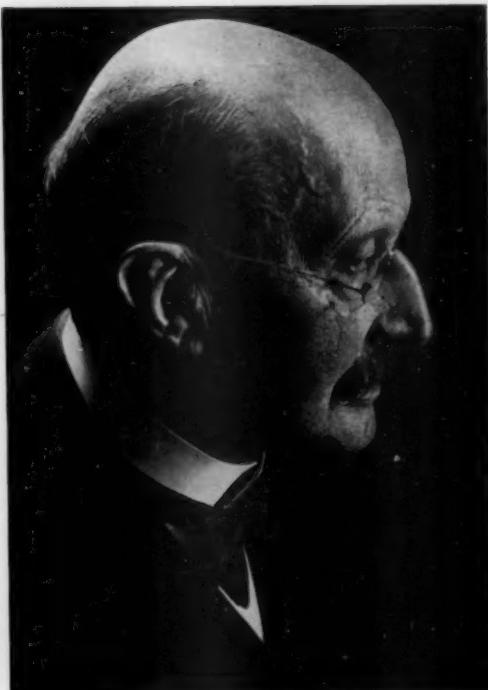
All of this was quite clear to me shortly after the appearance of Planck's fundamental work; so that, without having a substitute for classical mechanics, I could nevertheless see to what kind of consequences this law of temperature-radiation leads for the photoelectric effect and for other related phenomena of the transformation of radiation-energy, as well as for the specific heat of (especially) solid bodies. All my attempts, however, to adapt the theoretical foundation of physics to this (new type of) knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built. That this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instinct and tact to discover the major laws of the spectral lines and of the electron-shells of the atoms, together with their significance for chemistry, appeared to me like a miracle—and appears to me as a miracle even today. This is the highest form of musicality in the sphere of thought.

My own interest in those years was less concerned with the detailed consequences of Planck's results, however important these might be. My major question was: What general conclusions can be drawn from the radiation-formula concerning the structure of radiation and even more generally concerning the electro-magnetic foundation of physics? Before I take this up, I must briefly mention a number of investigations which relate to the Brownian motion and related objects (fluctuation-phenomena), and which in essence rest upon classical molecular mechanics. Not acquainted with the earlier investigations of Boltzmann and Gibbs which had appeared earlier and actually exhausted the subject, I developed the statistical mechanics and the molecular-kinetic theory of thermodynamics which was based on the former. My major aim in this was to find facts which would guarantee as much as possible the existence of atoms of definite finite size. In the midst of this I discovered that, according to atomistic theory, there would have to be a movement of suspended microscopic particles open to observation, without knowing that observations concerning the Brownian motion were already long familiar. The simplest derivation rested upon the following consideration. If the molecular-kinetic theory is essentially correct, a suspension of visible particles must possess the same kind of osmotic pressure fulfilling the laws of gases as a solution of molecules. This osmotic pressure depends upon the actual magnitude of the molecules, i.e., upon the number of molecules in a gram-equivalent. If the density of the suspension is inhomogeneous, the osmotic pressure is inhomogeneous, too, and gives rise to a compensating diffusion, which can be calculated from the well-known mobility of the particles. This diffusion can, on the other hand, also be considered as the result of the random displacement—unknown in magnitude originally—of

the suspended particles due to thermal agitation. By comparing the amounts obtained for the diffusion current from both types of reasoning, one reaches quantitatively the statistical law for those displacements, i.e., the law of the Brownian motion. The agreement of these considerations with experience, together with Planck's determination of the true molecular size from the law of radiation (for high temperatures), convinced the skeptics, who were quite numerous at that time (Ostwald, Mach) of the reality of atoms. The antipathy of these scholars towards atomic theory can indubitably be traced back to their positivistic philosophical attitude. This is an interesting example of the fact that even scholars of audacious spirit and fine instinct can be obstructed in the interpretation of facts by philosophical prejudices. The prejudice—which has by no means died out in the meantime—consists in the faith that facts by themselves can and should yield scientific knowledge without free conceptual construction. Such a misconception is possible only because one does not easily become aware of the free choice of such concepts, which, through verification and long usage, appear to be immediately connected with the empirical material.

The success of the theory of the Brownian motion showed again conclusively that classical mechanics always offered trustworthy results whenever it was applied to motions in which the higher time derivatives of velocity are negligibly small. Upon this recognition a relatively direct method can be based which permits us to learn something concerning the constitution of radiation from Planck's formula. One may conclude in fact that, in a space filled with radiation, a (vertically to its plane) freely moving, quasi-monochromatically reflecting mirror would have to go through a kind of Brownian movement, the average kinetic energy of which equals  $\frac{1}{2}(R/N)T$  ( $R$  equals constant of the gas-equation for one gram-molecule,  $N$  equals the number of the molecules per mol, and  $T$  equals absolute temperature). If radiation were not subject to local fluctuations, the mirror would gradually come to rest, because, due to its motion, it reflects more radiation on its front than on its reverse side. However, the mirror must experience certain random fluctuations of the pressure exerted upon it due to the fact that the wave-packets, constituting the radiation, interfere with one another. These can be computed from Maxwell's theory. This calculation, then, shows that these pressure variations (especially in the case of small radiation-densities) are by no means sufficient to impart to the mirror the average kinetic energy  $\frac{1}{2}(R/N)T$ . In order to get this result one has to assume rather that there exists a second type of pressure variations, which cannot be derived from

Maxwell's theory, which corresponds to the assumption that radiation energy consists of indivisible point-like localized quanta of the energy  $h\nu$  (and of momentum  $[h\nu/c]$ , [ $c$  equals velocity of light]), which are reflected undivided. This way of looking at the problem showed in a drastic and direct way that a type of immediate reality has to be ascribed to Planck's quanta, that radiation must, therefore, possess a kind of molecular structure in energy, which of course contradicts Maxwell's theory. Considerations concerning radiation which are based directly on Boltzmann's entropy-probability-relation (probability taken equal to statistical temporal frequency) also lead to the same results. This double nature of radiation (and of material corpuscles) is a major property of reality, which has been interpreted by quantum mechanics in an ingenious and amazingly successful fashion. This interpretation, which is looked upon as essentially final by almost all contemporary physicists, appears to me as only a temporary way out.



Tita Bins, Heidelberg  
MAX PLANCK, 1858-1947

# Fifty Years of Quantum Theory<sup>1</sup>

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THE LIFE OF MAX PLANCK and his great discovery have been treated in a separate essay, and we shall limit the present discussion to the consequences of his discovery—consequences which, one may say without exaggeration, have formed the principal subject of the experimental and theoretical research of the past fifty years.

We believe that we should consider in detail the developments in the first twenty-five years, which have already faded from the memory of our contemporaries, who are under the influence of the fundamentally more important results of the past twenty-five years. Since it has proved impossible to present a complete bibliography, only occasional references to literature will appear in the text.

## Part A. THE FIRST TWENTY-FIVE YEARS

Planck himself originally believed that the quantum hypothesis of radiation should be limited to the statistics of radiation exchange. Even in 1910 he mentioned that its application to the theory of the specific heat of matter seemed problematical to him. Not so to Einstein, who postulated in 1905 that a quantum  $h\nu$  was involved in the case of the individual processes of photo-effect and fluorescence. He soon extended this postulate by assigning to the photon not only the energy  $h\nu$ , but also the momentum  $h\nu/c$ . In 1912 he formulated the law of photochemical equivalence from which originated what may be called a new discipline—quantum-photo-chemistry.

Einstein's theory of specific heat is based on the formula of Planck's resonator, assuming that the single molecules of the solid body oscillate independently of each other. At high temperatures this theory leads correctly to Dulong-Petit's law, as well as to the known exception for hard substances such as diamond. However, at low temperatures the theory predicts a decrease toward zero that is much faster than the measurements of Nernst and his collaborators indicated.

In 1912 P. Debye distributed the energy quanta  $h\nu$ , not over individual molecules, but over the independent normal oscillations of the solid, again according to the temperature dependence of a Planck resonator, whereas the solid body itself was treated as a classical continuum. Atomism, in this case, is established only in an ingenious prescription for a cutoff: the classical spectrum of elastic "eigenvibrations" of the solid body is cut off where  $\nu = \nu_{\max}$  in such a way

<sup>1</sup> Translated from the German by members of the Department of Physics, Purdue University.

that the number of proper frequencies becomes equal to the number of degrees of freedom of the molecular structure of the solid. The resulting  $T^3$  law of specific heats and the characteristic temperature,  $\theta = h\nu_{\max}/k$ , are quantitatively in agreement with the experiment.

Debye, as early as 1910, had derived Planck's law of black-body radiation by means of a similar procedure. Again he distributed the energy quanta  $h\nu$ , according to statistical laws, over the electromagnetic "eigenvibrations of the Rayleigh-Jeans cube" and thus arrived at the spectrum of black radiation—this time without cutoff, because the number of degrees of freedom in this instance is unlimited.

A particularly impressive proof for the reality of energy quanta was given in 1913 by the experiment of James Franck and Gustav Hertz: electrons of precisely known energy passed through mercury vapor at low pressure. At an accelerating voltage of 4.9 the Hg-resonance line,  $\lambda = 2537 \text{ \AA}$ , appeared for the first time; with increasing voltage the remaining Hg-lines were excited. The excitation energy of the resonance line is thus 4.9 ev, which agrees exactly with the  $h\nu$  of the excited wavelength  $\lambda = 2537 \text{ \AA}$ . Later the same behavior in other atoms was confirmed in innumerable cases (first tabulated by Foote and Mohler, *Origin of Spectra*, in 1922).

Through the cooperation of spectroscopists of all nations there was available an enormous amount of information on measurement of wavelengths, the most intimate manifestations of atoms. A first attempt at order<sup>2</sup> was the separation of the wave numbers into two terms by J. R. Rydberg. W. Ritz, through his combination principle, showed that each term had a physical reality of its own: the difference of any two terms of an atom gives in turn another line of the atom (actual or observed only under certain conditions). This principle was first proved by Paschen in the infrared series of hydrogen. No expert could doubt that the problem of the atom would be solved if one should learn to understand "the language of spectra."

We read in the beautiful biography of Carl Runge, the eminent spectroscopist and highly gifted mathematician, that he took every opportunity to learn the opinion of leading physicists regarding the possible interpretation of the curious series law which he had studied with H. Kayser. Thus he once called on Helmholtz and presented him with the manuscript of a treatise in this field. Helmholtz sat quietly in thought and then said, as if to himself: "Yes, the planets! How would that be? The planets . . . but no, it won't

<sup>2</sup> The simplest example is the well-known Balmer series.

do?" Runge continues his description of this visit: "I could not imagine them in what manner the planets were connected with the matter. But later I realized that he had obviously thought of the orbits of electrons around the nucleus."

We do not wish to be as imaginative as Runge and ascribe to Helmholtz the prediction of E. Rutherford's atom nucleus and N. Bohr's nonradiating orbits. However, let us consider the last part: "It won't do." This indeed was the point of view generally taken by physicists confronted with the unbelievable riddle posed by the spectroscopy for classical physics: the convergence of series lines in a limit, the relation of the series among themselves, their transition to the continuous spectra, etc.

It took many new ideas to solve the mystery: Planck's discovery of  $\hbar$ , the ingenious visualization of the atomic nucleus by Rutherford, as well as the daring postulates of young Niels Bohr on the stability of the atom; the nonradiating quantized electron orbits, the interpretation of series terms as energy levels (after multiplication by  $\hbar$ ), and their differences as energy of the emitted light quanta. When F. Paschen presented Bohr's first paper (*Phil. Mag.*, 26, 1913) in his laboratory in Tuebingen, he said: "This may be the most important paper in physics for the next decades."

For the H-atom it was sufficient to introduce one quantum number, the azimuthal quantum number. As J. Nicholson had done before Bohr, one sets the angular momentum " $p$ " of the electron equal to a multiple of  $\hbar/2\pi$ . This follows as a special case from the general quantization of the phase integrals  $\oint pdq = nh$  derived in 1915 by W. Wilson from the theory of heat radiation and applied almost simultaneously by him and A. Sommerfeld to the hydrogen spectrum. Besides the azimuthal number one must consider a "radial quantum number."<sup>19</sup> Whenever a direction in space is distinguished—e.g., by a magnetic field—a third number is added, the magnetic quantum number, which in 1916 led to a provisional understanding of the normal Zeeman effect. Simultaneously K. Schwarzschild and P. S. Epstein treated the Stark-effect of hydrogen by introducing parabolic coordinates and two parabolic quantum numbers, besides an azimuthal quantum number. By doing so they arrived at a complete reproduction of the experimental findings in regard to number and position of the components.

The quantum theory even threw light on that greatest of mysteries of chemistry, the periodic system of elements. Bohr conceived the electrons as being successively "caught" with increasing nuclear charge. Thus he was able to explain the shell structure of

<sup>19</sup> Calculation by means of the phase integral assumes, however, that the momentum  $p$  for each coordinate  $q$  be a pure function of  $q$  (case of separability). Thus the phase integral is a special case of the finiteness of the phase element:  $\oint dp dq = \hbar$  introduced earlier by Planck as a criterion of statistically indistinguishable cases, and nowadays basic for every statistics (e.g., the Sackur-Tetrode formula).

the atoms and, with the help of spectroscopic and x-ray-spectroscopic data, the correct sequence of atoms within the periodic system, such as the order of K, Ca, up to the closure of the  $M$ -shell. The shell structure is defined by the principal quantum number  $n$  (the sum of the three quantum numbers mentioned previously). In 1925 E. C. Stoner divided the shells correctly into subdivisions, and the shell closure was definitely determined by the Pauli exclusion principle. However, for this a fourth quantum number was needed,  $m_s = \pm \frac{1}{2}$ , now called the spin quantum number. The period numbers  $2 \times 1^2, 2 \times 2^2, 2 \times 3^2, 2 \times 4^2, \dots$  predicted somewhat alchemistically by Rydberg were thus explained through Pauli's postulate that each electron state (completely defined by the four quantum numbers mentioned) can appear only once in an atom. The same rule also holds for electrons in molecules, crystals, conduction electrons, etc.

We return now to the systematics of "hydrogenlike" spectra. The fundamental experiment by O. Stern and W. Gerlach (1921) demonstrates a clearly recognizable consequence of the spin quantum number  $m_s$ , the spatial orientation of the magnetic moment connected with the spin. An atomic beam of vaporized Ag (or gaseous H, etc.), appropriately collimated, is deflected in an inhomogeneous magnetic field. This experiment shows that the atomic unit of magnetic moment is Bohr's magneton, predicted quantum-theoretically, and not the "Weiss magneton," expected and one fifth as large. The Stern-Gerlach effect has the basic advantage of being related to one state of the atom, the ground state, and not to a combination of both states, as is the Zeeman effect. The magnetic field in the Zeeman effect influences both states. Only by using the combination principle (T. van Lohuizen, 1919; A. Sommerfeld, 1920) is it possible to draw conclusions regarding the magnetic behavior of the initial and final state of the atom.

In 1916, application of relativistic mechanics showed that the Balmer terms, single according to ordinary mechanics, are relativistically separated into groups of neighboring components, and that the spacings between them are determined by the fine

structure constant:  $a = e^2/\hbar c \sim \frac{1}{137}$ . Spectrograms of ionized helium taken at this time by Paschen showed more than qualitative agreement with the theory. The relativistic fine structure in H finds its counterpart in non-hydrogenlike spectra in the separation into principal and subordinate series. It is to be hoped that once the connection between  $e$  and  $\hbar$ , established through the value  $a$ , is theoretically clarified, it will lead to a more thorough understanding of the relations that seem to exist between the quantum of charge ( $e$ ) and the quantum of action ( $\hbar$ ).

In order to disentangle the spectra, not only must the term values be known, but also their possible combinations. These are governed by certain selection rules, which take into consideration only the possibility or impossibility of combination. The "transition-

probabilities" calculated later by wave mechanics accomplished more. The value 0 indicates that a combination is forbidden; a value  $> 0$  indicates that a combination is allowed and gives the expected intensity of emission.

If we confine ourselves to a one-electron system (e.g., alkali atom), the selection rules are: the azimuthal quantum number—called in wave mechanics  $l$ —can change only by  $\Delta l = \pm 1$ . There are no restrictions for the radial quantum number. For the "inner quantum number" the selection rule is:  $\Delta j = \pm 1$  or 0. Let us discuss briefly the origin and meaning of quantum number  $j$ . This number (*Ann. Physik*, 63, 221, [1920]) originated from the structure of the so-called "complete doublet and triplet" analyzed by Rydberg. This consists in the doublet system of three, and in the triplet system of six components (principal lines and satellites.) The choice of the name "inner quantum number" is not a happy one, since it seems to point to a hidden characteristic of the atomic nucleus. Actually  $j$  represents the total resultant angular momentum of the atom. In the single electron case it is the resultant of the orbital angular momentum  $l$  and the spin momentum  $m_s = \pm \frac{1}{2}$ , and is  $j = l \pm \frac{1}{2}$ . Hence it follows necessarily from the conservation of areas, but is by no means a concealed constant of motion. The generalization of this definition for many-electron systems will be discussed later.

As can be seen from the preceding discussion, the selection rules had to be conjectured from spectroscopical data, and then adequately generalized. This was made possible only by the extraordinary precision of spectroscopic data. An approach that proved theoretically more satisfactory was found in Bohr's correspondence principle. This follows from considering radiation with large quantum-numbers (Fourier representation applied to the angle-coordinates first introduced by K. Schwarzschild) and uses the possibilities of combination found there in the case of small quantum numbers. The uncertainty of conjecture is thereby substantially reduced. H. A. Kramers, especially, has shown the value of this method.

In the many-electron system the salient point is the coupling of the individual  $l$  and  $m_s$ . (This concerns only outer valence-electrons; the inner electrons form closed shells with momentum zero, according to the Pauli principle.) The spin vectors  $m_s$  add algebraically to a resulting spin  $S$ , an integer or half-integer, depending on whether the number of electrons is even or odd. The orbital moments  $l$  add vectorially to form a resulting total moment  $L$ , an integer.  $L$  and  $S$  combine vectorially to form the resultant total angular momentum  $J$ . This is the normal or Russell-Saunders coupling.  $J$ , like  $S$ , is integral or half-integral, and thus follows the alternation or displacement law, which is valid throughout the periodic system: the spectra are, with regard to the quantum number  $J$ , integral or half-integral, depending on

whether the number of electrons in the atom is even or odd. The doublet system of the alkalies is followed by the singlet- and triplet-system of the alkaline earths, the doublet- and quartet-system of the elements in the third column of the periodic table, the singlet-triplet- and quintet-system in the fourth column, etc. This is valid all through to the very beginning of the periodic system. Hydrogen has a (relativistic) doublet spectrum. The helium spectrum consists of triplet lines (orthohelium) and singlet lines (parhelium). The selection rules for  $L$  and  $J$  are similar to those for  $l$  and  $j$ . In 1922, when Sommerfeld was lecturing at Harvard University on the selection rules, F. A. Saunders, who was present, confirmed, with satisfaction, that certain combinations of singlet and triplet terms for which he had looked in vain in the Ca spectrum were impossible because of these selection rules. The term notation now generally<sup>4</sup> adopted fits the Russell-Saunders coupling. According to the value of  $L$  the terms are called  $S, P, D, F, G, H, \dots$  ( $L = 0, 1, 2, \dots$ ) The superscript on the left indicates the multiplicity of the term ( $r = 1$ , singlet;  $r = 2$ , doublet, etc.), whereas the subscript on the right refers to the quantum number  $J$  of the level in question. For instance, the ground term of the iron spectrum is a quintet  $D$ -term  $^5D_J$ , where  $J$  can have the values 4, 3, 2, 1, 0, and where  $J = 4$  represents the lowest term.

The complex line groups resulting from the combination of multiplet terms (a generalization of Rydberg's complete doublets and triplets) were known first through M. A. Catalan, who called them multiplets, and were found in the London laboratories by A. Fowler in an investigation of the Mn-spectrum. Following this study a rich multiplet literature developed. The disentanglement of the iron spectrum by O. Laporte (Diss., Munich [1924]) and F. M. Walters (*J. Optical Soc. Am.* [1924]) is a masterpiece in this field. Laporte's work was considerably aided by the results on the Zeeman effects of the iron lines of the solar spectrum, made available by H. D. Babcock, Sr., of the Mount Wilson Observatory. The iron spectrum consists of combinations and intercombinations of the quintet-septet-triplet-systems. The spectra of the rare earths, already analyzed in part, are still more complicated than the iron spectrum.

Another achievement of brilliant and bold induction was Landé's  $g$ -factor (1923), which regulates the anomalous Zeeman effects of any given multiplicity and any given quantum number  $L$ . This finding was prepared experimentally by the masterly magneto-optical measurements of E. Back.

Besides the energy levels of multiplets, it was also possible to predict theoretically their relative intensities. This was partially accomplished with the aid of the correspondence principle, and partially through the knowledge of the sum rules which the Utrecht

<sup>4</sup> Compare in particular the atomic energy levels of the Bureau of Standards by Charlotte E. Moore and W. F. Meggers (1949).

laboratory (L. S. Ornstein, H. C. Burger, H. B. Dorgelo) investigated systematically. These efforts were crowned by the establishment of general intensity formulas, valid for any given multiplets, and found simultaneously and independently in three different places: H. N. Russell (*Nature*), R. de L. Kronig (*Z. Physik*), A. Sommerfeld and Hönl (*Preuss. Acad.*). The most significant application of these formulas was made by Russell, who determined the abundance of various elements in the sun from the intensity of their multiplets. More recent calculations by Unsöld could not substantially improve Russell's results.

F. Hund presented a complete system of these complex spectra. He and R. S. Mulliken applied similar principles to the band spectra of molecules. Other couplings besides that of Russell-Saunders are feasible: the  $(jj)$ -coupling seems especially important for the structure of nuclei.

The scheme sketched here seems to satisfy the practical needs of spectroscopy. Although there still exist some inconsistencies (concerning even the simple atoms H and He), and although a number of questions (such as the mutual disturbance of neighboring multiplets) remains to be discussed, the enormous body of material on wavelength measurements is now organized systematically with the help of integral and half-integral quantum numbers. The rules and designations described here will remain useful for practical applications. Even though the early naive ideas had to yield to more abstract concepts, the conclusions drawn from them were confirmed to a large extent by developments during the next twenty-five years and have been but slightly changed.

Similar to the situation in the optical field is the situation in the field of x-rays. After the discovery of crystal analysis in 1912, the problem of the series connected with  $K$ ,  $L$ ,  $M$ -radiation was quickly solved. The experimental material was firmly anchored under the guidance of M. Siegbahn, was organized by means of the combination principle (W. Kossel), and applied to the periodic system (H. G. J. Moseley). Again, the relativistic doublet formula proved itself correct on a considerably enlarged scale because of the nuclear charge. These results must be considered as lasting and can hardly be changed by any possible refinements of quantum mechanics.

The establishment of a short-wave limit of the continuous x-ray spectrum by Duane-Hunt and D. L. Webster in 1915 was especially significant because it pointed directly to Einstein's light quanta. This was demonstrated still more convincingly by A. H. Compton's great discovery (1923), which left no possible doubt regarding the reality of wave and particle.

#### Part B. THE PAST TWENTY-FIVE YEARS

Today's quantum theory originated from the discussion of two questions, leading by two different paths to the same goal. One approach is characterized by the names of L. de Broglie, E. Schrödinger and C. J.

Davison, and L. H. Germer; the other has been developed by W. Heisenberg, M. Born and P. Jordan, and last, but not least, by N. Bohr and W. Pauli. Both paths meet again in the work of P. A. M. Dirac.

In interpreting the Compton effect as a collision between a light quantum (considered as a particle) and an electron, an old question again became urgent: How can one understand light interference produced by a diffraction grating according to quantum theory? W. Duane pointed out in 1923 that a diffraction grating, considered as a periodic mechanical system and quantized according to Bohr-Sommerfeld, can only absorb discrete recoil momenta which, by the law of conservation of momentum, lead to specific deflections that correspond to the directions of constructive interference.

If the quantum conditions for the grating lead to interference, it must be irrelevant whether quanta or particles are diffracted by the grating. One can easily verify that thus any particles scattered by the grating behave like waves with a wavelength  $\lambda = \frac{h}{p}$  ( $p$  = momentum). This is exactly the relation which de Broglie postulated in 1924 as a relativistic corollary to Planck-Einstein's equation  $E = h\nu$ .

True, the objective of de Broglie is the opposite of that of Duane. De Broglie wanted to understand the quantum conditions as a consequence of interference phenomena; and he could show that the latter can be derived from the postulate that the wave train associated with a particle must include a whole number of wavelengths in a closed orbit.

As early as 1925, W. Elsasser drew attention to investigations of the Ramsauer-effect (scattering of slow electrons by atoms) and to experiments by C. J. Davison and C. H. Kunsman (1923) on the reflection of electron beams from single crystals, as indications of particle interference. But only in 1927, about one year later than Schrödinger's first paper, the improved measurements by C. J. Davison and L. W. Germer brought the definitive experimental proof of the reality of de Broglie's waves. Shortly afterward, G. P. Thomson and A. Reid obtained the first Debye-Scherrer pictures with electron beams. The wave properties of protons and atoms were demonstrated in 1928 in studies by Th. H. Johnson, F. Knauer, and O. Stern, and by I. Estermann and O. Stern.

As mentioned earlier, Schrödinger formulated de Broglie's hypothesis mathematically with unsurpassed skill, prior to the experimental verification of matter waves. The basis of Schrödinger's investigation is the understanding that, besides the de Broglie relation between wavelength and momentum, the classical equations of motion for massive particles must follow from the proposed wave theory of electrons as an approximation that corresponds to geometrical optics. Indeed, if one accepts the additional hypothesis that matter waves (as contrasted to electromagnetic waves) are represented by one single scalar wave function  $\psi$ , Schrödinger's nonrelativistic wave equa-

tion for an electron in a potential field is uniquely determined as

$$\Delta \psi + \frac{2m}{\hbar^2} (E - V) \psi = 0.$$

In spite of the fact that this hypothesis must be corrected later on, Schrödinger's method worked very well, especially for the derivation of Bohr's equation for energy levels in the hydrogen atom:

$$E = \frac{\hbar \cdot c \cdot Ry}{n^2}.^5 \text{ The exclusion of the quantum number}$$

$n=0$  follows automatically, whereas it was obtained only empirically in the old quantum theory. Deviating from the older quantum theory, the energy terms for the oscillator and rotator have become

$$E = \hbar \omega (n + \frac{1}{2}) \text{ and } E = \frac{\hbar^2}{2\mu} l(l+1).^6 \text{ The new formulae}$$

agree with experimental fact and are identical with the results of matrix mechanics. The modified rotator equation had been deduced earlier, empirically, from band spectra.

The frequencies of the eigenvibrations of the electron waves in the atom are determined by the energy terms. However, the nature of the wave function  $\psi$ —(just what is oscillating?)—is unknown at first. It had been known, of course, that the phase  $S$ , of the generally complex wave function  $\psi = / \psi e^{iS}$  is closely connected with the action function of particle mechanics. What is, then, the quantity  $/\psi$ ? From the time independence of the integral  $\int \psi^* \psi d\tau$  (taken over all space) it follows that this same integral represents a quantity which is conserved in the course of motion just like the charge of the electron. This quantity will have to be related to the charge. Schrödinger assumed at first that  $\psi^* \psi$  is the density of the continuously spread-out charge of the electron. This concept had to be rejected, because the charge density of a free particle would soon diffuse. For later discussions it should be kept in mind that the space integral over the density,  $\psi_m^* \psi_n$ , obtained from two solutions of Schrödinger's equation, is constant.

Further progress in wave mechanics came about only in connection with Heisenberg's matrix mechanics, already formulated in 1925 before Schrödinger's discovery. The sum rules (Part A), the derivation of the selection rule from the correspondence principle, as well as the estimation of intensities of spectral lines, had shown that the formulas of classical electrodynamics, for the intensity of radiation of revolving or oscillating charges, must also find their place in quantum mechanics. Heisenberg recognized the possibility of retaining those formulas and saw that the question to be asked was: which quantities must be substituted for frequency and amplitude of oscillation

<sup>5</sup>  $E$ , the energy;  $\hbar$ , Planck's quantum;  $c$ , the light velocity;  $Ry$ , the Rydberg constant;  $n$ , the principal quantum number.

<sup>6</sup> These expressions approach, for large quantum numbers,  $n$  and  $l$ , Bohr's formulas (correspondence principle).

under the changed condition of quantum mechanics? According to Bohr's theory, it was to be expected from the very beginning that these quantities could not be related directly to electron orbits, but to transitions between two stationary states (of Bohr's atom), and that the frequency  $\omega_{nm}$  of the emitted quantum must be substituted for the orbital frequencies. Thus the "transition amplitudes"  $X_{mn}$  could be determined empirically. Heisenberg was able to derive the laws for  $X_{mn}$  from Thomas-Kuhn's sum rule and from considerations following from the correspondence principle. The formulation of these laws is particularly simple, if one writes the amplitudes for all transitions as matrices. First, because in this case the ordinary equations of motion hold for the matrices if one substitutes matrices for the coordinates, and if multiplication means matrix multiplication. Second, between the amplitudes  $x$  and the transition momentum  $p = mx$ ,

commutation relations hold:  $px - xp = \frac{\hbar}{i} I$  ( $I$  = unit matrix) which are integrals of the equation of motion and follow directly from the Thomas-Kuhn sum rule.

Next to Heisenberg, science is indebted to M. Born and P. Jordan (1926) for the development of the formalism of matrix mechanics. Born went further and found the bridge leading to wave mechanics. He interprets  $\psi^* \psi$  (unlike Schrödinger) as probability density, so that diffusion of density means that the designation of the position of a free particle in the course of time becomes less and less determinate. Correspondingly, the transition density  $\psi_m^* \psi_n$ , mentioned above, characterizes the transition between two quantum states and permits the calculation of Heisenberg's matrix elements. Thus, for wave mechanics the calculation of intensities became possible. The atom had now become accessible to the elegant methods of analysis. Despite his dislike of the statistical reinterpretation of his beautiful wave picture, Schrödinger himself, as well as C. Eckart, soon proved the mathematical equivalence of wave mechanics and matrix mechanics.

Before proceeding to the numerous problems that could now be solved one after another, we must dwell on some attempts to interpret quantum mechanics, which are so profound that, to use Heisenberg's expression, it is no longer merely a matter of understanding physics, but a matter of "philosophical position."

First to be considered are the discussions in Copenhagen between Bohr and Heisenberg, which resulted in Heisenberg's formulation of the uncertainty principle and Bohr's concept of complementarity. Considered in this way the ideas of waves and "articles" are basic concepts that complement each other. Both describe a piece of reality in the same way as does the projection of a three-dimensional object on two planes, where alternately one or the other projection may give a better picture, but never a complete picture of reality. Their limitation is determined by the uncertainty principle, according to which it is not

possible to determine accurately and simultaneously both position and momentum.

During the Solvay Congress of 1927 an even more profound question was discussed by Einstein and Bohr. This can be described with the help of the previous analogy of double projection as follows: Is it possible to unite the pictures obtained on the projection planes into one concept or image embracing both? Although such a union is possible, mathematically, without contradiction by quantum mechanics, no answer could be found that would satisfy all physicists. Lately, those discussions have been revived in articles of Bohr and Einstein in the publication honoring Einstein's seventieth birthday.<sup>7</sup> Bohr was able to refute Einstein's objections, which were presented in the form of hypothetical experiments; Einstein apparently did not succeed in completely presenting the central points of his criticism in the form of these hypothetical experiments. These differences in comprehension cannot be disposed of lightly in the manner of the wise resignation that Planck expressed in his autobiographical annotations (*Naturwissenschaften*, 1947); namely, by pointing to a "difference in generation."

An essential contribution to the interpretation of quantum mechanics, preceding the Copenhagen discussions, is the statistical transformation theory which originated with Dirac and Jordan. Every complete set of quantities simultaneously and exactly observable forms a possible basis for the transformation theory—e.g., the position coordinates in the simple Schroedinger equation. At a given moment these quantities are statistically described by the wave function, in this connection called "probability amplitude." A wave function of this kind changes in the course of time within a free physical system, or during measurements, because of the interaction with the measuring instrument. The change, mathematically, is a transformation of the wave function, which is uniquely defined because of the process or because of the experimental arrangement, and which becomes an objective expression of the nature of the system or of the interference in the act of measuring, independent of any philosophical point of view.

J. v. Neumann, in 1927, was able to derive yet another important conclusion from the statistical transformation theory. Purely descriptively the motion of an electron resembles the Brownian movement of a colloidal particle in a gas. Therefore consideration has been given to interpreting the statistical character of quantum mechanics as a result of the coupling of atomic particles with a statistical system, unknown, but corresponding to the gas in question. J. v. Neumann has shown that any assumption of this kind leads to fluctuations other than those predicted by quantum mechanics.

Fundamental to quantum mechanics is the discussion of electron spin. With the help of Sommerfeld's

inner quantum numbers (1920–21), it was possible to understand the multiplet structure of spectral lines. Pauli had insisted quite early that this must be the manifestation of an electron property which, in turn, led S. Goudsmit and G. E. Uhlenbeck in 1925 to the hypothesis that the electron must have its own spin momentum of the magnitude  $\frac{\hbar}{2}$  and a magnetic moment

(Bohr's magneton)  $\frac{e\hbar}{2mc}$ . Pauli, in 1927, opened the way to successful wave mechanical treatment of the spin by the assumption of two wave functions. Thus, one must abandon Schroedinger's hypothesis that the wave function has only one scalar component. The other two fundamentals of the wave equation—the de Broglie-relation and the identity between the approximation of geometrical optics and classical mechanics—remained unimpaired. Thus the spin becomes an essential quantum mechanical characteristic with nothing comparable in the classical approach.<sup>8</sup>

The entire development was completed in 1928 in a perfect manner by Dirac's relativistic wave equation of the electron. This wave equation combined four components of the wave function by a system of four linear partial differential equations of first order. The effect of Dirac's equation on spectroscopy is to surpass Pauli's equation in the confirmation and refinement of Sommerfeld's formula for the hydrogen fine structure. Its significance, however, reaches farther, since in later years there has been the understanding that different particles correspond to different wave equations. The wave equations of the meson by A. Proca, H. Yukawa, and N. Kemmer can serve as examples.

Heisenberg's work on He (1926) is, next to the calculation of intensities, one of the first applications of quantum mechanics. Here it became evident that the new theory was adapted to the quantitative treatment of many-body problems. This first, simple example led to the central concept of "exchange force," which has to do with the fact that the average energy of both electrons in the atom depends on the probability with which the electrons can approach each other (correlation). Whereas the analogous question concerning phase relations between two rotating electrons could not be solved with the older quantum theory, wave mechanics offered certain correlations, that is, the symmetry or antisymmetry in the position coordinates of the wave functions. The two types of solution led to the empirical term systems of ortho- and parahelium.

The hydrogen molecule can be handled in similar manner, assuming the heavy hydrogen nuclei to be at rest, since in this case, one must deal with two electrons in a fixed potential field. Here again one arrives at two-term systems, the energy values of which depend, furthermore, on the distance between protons.

<sup>7</sup> Albert Einstein: *Philosopher-Scientist*. The Library of Living Philosophers, Vol. VII (1949).

<sup>8</sup> Lately, the possibility of correcting this viewpoint by means of the theory of elementary particles has slightly increased.

In 1927 F. London and W. Heitler were able to show that the energy of the lowest state becomes smaller at first as the protons approach each other, and only at very small distances does it increase rapidly. The resulting attraction explains the homopolar chemical bond. This created the basis for quantum chemistry, which was developed further by J. C. Slater and L. Pauling, and in particular by E. Hückel, who was able to explain the conjugated double bond (benzene ring). It also established a basis for the theory of molecular spectra (F. Hund, R. S. Mulliken, E. Wigner, *et al.*). In these investigations methods of group theory were useful. Heisenberg was able to show in 1928 that the Weiss force in ferromagnets is due to an exchange force between electrons; and F. Bloch in 1930 successfully applied the method of Heitler-London to electrons in ferromagnetics.

All these investigations are based on the Pauli principle (*Part A*). This means, expressed in terms of wave mechanics, that the total wave functions, depending on position and spin coordinates, must necessarily be antisymmetric. In quantum mechanics it appears as an empirical law that is consistent with the fundamental requirements. It could only be proved, by Pauli, in quantum theory of wave fields (*Rev. Modern Phys.* [1941]). A direct experimental confirmation is given by collision experiments with like particles (N. F. Mott's collision formula).

As in classical mechanics, the three- and many-body problem in quantum mechanics can be attacked only by means of approximation methods. In wave mechanics, such methods were developed by L. H. Thomas and E. Fermi (1928), and by D. R. Hartree and V. Fock (1928), and used for the calculation of atomic states. The first one is particularly convenient for many problems; it has been used for studies on heavy nuclei (Heisenberg, Solvay Congress, 1934), especially for investigating the saturation of nuclear forces.

The Fermi-Dirac statistics, already known in older quantum theory, is also based on the Pauli principle. Its application to conduction electrons in metals, which, in a first approximation, are treated as free particles, led Sommerfeld (1927-28) to a successful revival of P. Drude's theory of conductivity, as well as to an explanation of the Wiedemann-Franz law. The behavior of electrons in a lattice has been particularly studied by R. Peierls and F. Bloch (1930). Its most important result is the band structure of energy terms and the resulting classification of conductors, semiconductors, and insulators. Apparently the electrical resistance depends on the interactions between electrons and the irregular fluctuations of the potential in the lattice caused by thermal motion, impurities, and lattice defects (residual resistance at low temperatures). Lately, interest has been directed toward phosphors and semiconductors, which are important for technical applications. The problems of superconductivity and superfluidity have not yet been solved completely.

As early as 1927 Hund pointed to the predissocia-

tion of molecules in an electrical field as an example of the penetrability of the potential barrier by electrons, the energy of which is insufficient to surmount the barrier (tunnel effect). G. Gamow's theory of the  $\alpha$ -decay of radioactive atoms (1928) is another example. Here, for the first time, quantum mechanics is being applied to problems of nuclear physics. Only after the discovery of the neutron (1932) was it possible to deal systematically with nuclei and to consider both the neutron and the proton as elementary nucleons. On the basis of Heisenberg's hypothesis (1933), the force between them could be considered as the result of an exchange of charge, whereby the particles constantly interchange roles. The fundamental problem of nuclear physics, to derive the elementary forces between nucleons from the behavior of atomic nuclei, has not yet been solved completely, in spite of many successful solutions of special problems (H. A. Bethe, *Rev. Modern Phys.* [1937-38]; L. Rosenfeld, *Nuclear Forces*, New York [1948]). According to general opinion, the difficulties are closely connected with problems of the theory of elementary particles. For this reason, the explanation of the "Magie Numbers" by Mrs. M. Goeppert-Mayer in America and by O. Haxel, H. E. Suess, and J. H. D. Jensen in Germany (1949) is especially gratifying. According to this, the nucleons in the densely packed nucleus can be considered as independent particles, moving in an average potential field.

Up to now, Bohr's frequency condition and the formula for the emitted intensity have not yet been made an integral part of quantum mechanics, although Jordan showed, in 1925, that this could be achieved by the application of quantum mechanics to the proper frequencies of the radiation field. This idea took hold only after Dirac's comprehensive work on radiation theory in 1927. It also laid the foundation for the general theory of wave fields. It seems particularly remarkable that light quanta become countable, though not individually distinguishable carriers of radiation without the help of a new hypothesis (Bose-Einstein statistics). Essential are operators describing the emission and absorption of light quanta.

If one attempts, on this basis, to take up the entire problem of "electron and radiation" (Jordan-Wigner, Jordan-Pauli, Pauli-Heisenberg, around 1930), one soon is confronted with grave difficulties, which arise from the fact that it is not permissible to talk of point charge in the immediate vicinity of the electron. Especially must it be kept in mind that particles and quanta are constantly produced and annihilated, some virtually and temporarily, others in reality, as in the case of pair production discovered in 1932 by C. D. Anderson (predicted four years earlier by Dirac).

In spite of successes, even the recent ones of R. P. Feynman, S. Tomonaga, J. Schwinger, and F. J. Dyson, and in spite of the certainty that quantum electrodynamics is on the right road, a rigorous solution of the present basic questions leads to divergencies. In order to remove these divergencies, methods of

renormalization have been proposed which appear to be concealed changes of the basic equations not yet analyzed in detail.

It has been mentioned that the discovery of new elementary particles has led to new equations (Kemmer), similar to the Dirac equation, but with a different spin. Investigation of these shows that the general quantum theory of wave fields is still more problematical than quantum electrodynamics. This is partly due to the fact that the coupling between fields cannot be considered as small, so that the first approximation, the

only convergent one, does not yield a good representation of reality, even in accessible energy ranges.

Here we close this chronicle. Questions concerning "a possible smallest length," the relation between elementary particles, and Born's "Apeiron"—an all-encompassing concept of the laws of all elementary particles—do not yet belong to history but represent subjects of contemporary work which, it is to be hoped, will be as successful as that of the period we have discussed. May our times favor this pursuit of pure knowledge!



## Quantum Theory and Chemistry

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THE DEVELOPMENT OF THE SCIENCE OF CHEMISTRY during the first half of the twentieth century has been in great measure the result of the application of quantum theory to chemical problems. The history of quantum theory in chemistry during this period comprises nearly the whole of the recent history of the science in its theoretical aspects.

In 1900 chemistry was well developed as an art and as an empirical science, but it was replete with puzzles. Any chemist could ask hundreds of questions that no one could answer—questions as to the nature of matter and of chemical change, the structure of elements and compounds in the gaseous, liquid, and crystalline states, the mechanism of chemical reaction. The electron had been discovered, but it was not yet known that an atom contained, in addition to one or more electrons, a very small, heavy nucleus. Chemical valence was simply a part of the empirical structure of chemistry, with hardly more than a glimmering of structural interpretation, in terms of the transfer of electric charge that had been introduced by Berzelius a century before. The valence bond, fifty years after it had been brought into the chemical system by Cowper and Kekulé, remained just a line drawn between the symbols of two elements in a structural formula, or a coupled pair of hooks. Now, in 1951, nearly the whole of chemical science has been given an explanation, an interpretation, in terms of simple particles—electrons, nuclei, and light quanta—and simple, fundamental processes. The puzzling questions as to the nature of chemical substances and chemical reactions have been answered. There are still problems—many problems—in chemistry, but, with rare exceptions, they are problems rather than puzzles. We now understand the dimensional region of chemistry, the region involving lengths  $10^{-8}$  to  $10^{-7}$  cm. The great puzzles that nature now presents to us are

in the nuclear region, around  $10^{-12}$  cm, in the region of the gene, around  $10^{-8}$  cm, and in the region of universes, around  $10^{24}$  cm.

The first significant application of quantum theory to chemistry was made by Einstein, in his explanation, in 1907, of the decrease in heat capacity of substances at low temperature. In the formulation of the third law of thermodynamics by Nernst it was necessary to assume that the reactants and the products in a chemical reaction should, at very low temperatures, have no difference in heat capacity. It was found by experiment, by Nernst and Eucken, that indeed the heat capacity of solids decreases, apparently asymptotically toward zero, at very low temperatures, and Einstein pointed out that the statistical mechanical treatment of a quantized oscillator leads to a heat capacity curve which falls off toward zero, as observed. Greatly improved quantitative agreement with experiment was obtained by Debye, through the discussion of the spectrum of vibrational frequencies of the solid substance, and the theory was further refined by Born and Kármán. During the next fifteen years the statistical mechanical interpretation of the whole of thermodynamics was achieved, through the application of quantum statistical mechanics. One of the most recalcitrant problems, that of the heat capacity of gaseous hydrogen, was finally solved in 1926, by D. M. Dennison, through the introduction of the postulate of a frozen equilibrium between two kinds of molecular hydrogen, ortho hydrogen and para hydrogen.

Einstein was also responsible for the next application of quantum theory to chemistry, the formulation of the law of photochemical equivalence, the role of the light quantum in chemical reactions. This contribution, made by Einstein in 1912, with the stimulus of early efforts by Warburg (1907, 1909), which in turn were based on Einstein's introduction of the light

quantum in the treatment of the photoelectric effect, gave at once an explanation of the existence of a short-wavelength limit of light producing a chemical reaction, and of the amount of reaction produced by a given amount of light absorbed. The quantum theory has been fundamentally involved in all further developments of photochemistry—the development of the theory of molecular spectra and molecular structure, the Franck-Condon principle, the theory of photochemical chain reactions, and the special mechanisms involved in such important photochemical reactions as the photochemical fixation of carbon from carbon dioxide by chlorophyll.

Quantum theory has had great significance for practical chemical thermodynamics. The discovery of the ways of calculating the entropies of gases from spectroscopic and molecular structural data and of the residual entropy in some crystals, carbon monoxide, nitrous oxide, hydrogen, ice, etc., at very low temperatures has led to significant progress, and at the present time the best available free-energy data for many substances are those obtained by use of quantum mechanical calculations, rather than solely by direct experiment. Sackur and Tetrode, Eucken, F. Simon, Clausius, and especially Giauque have been great contributors to this work.

The most important periods in the development of chemical theory were the few years after the formulation of the Bohr theory of the atom, in 1913, and the few years after the discovery of quantum mechanics, in 1924. After Bohr and Sommerfeld had devised the methods of discussing the motion of electrons in atoms, with use of the old quantum theory, it became possible to interpret the greatest of all chemical generalizations, the periodic table of the elements, in terms of electronic structure. This step was taken by Bohr himself; a small refinement was introduced, largely on the basis of chemical data, by Main-Smith. Elementary electronic interpretations of chemical valence were formulated by Kossel and G. N. Lewis, in 1916. Kossel laid especial emphasis on the transfer of electrons from electropositive to electronegative atoms, with the resultant formation of ions, and quantitative calculations of predicted properties of ionic crystals were carried out by Madelung, Born, and Haber, with use of the concepts of ionization potentials, electron affinities, and the balancing of electrostatic attractive forces by characteristic repulsive forces between atoms. These calculations represented the first moderately successful effort to predict the properties of substances (enthalpy, entropy) from knowledge of their structure. G. N. Lewis was especially interested in the far greater class of non-ionic substances. In 1916 he introduced the concept of the chemical bond as a pair of electrons held jointly by two atoms, and he and Irving Langmuir showed that this postulate provided a satisfying basis for the systematization of a great amount of chemical knowledge.

During the period since 1913 powerful methods of

determining the structure of molecules and crystals have been developed. The first of these was the method of determining the structure of crystals by the diffraction of x-rays, which was originated in 1912 and 1913 by M. von Laue and W. H. and W. L. Bragg, and which, through application by a great many investigators, permitted during the following years the acquisition of a very great amount of structural information. This has assisted in the clarification of the structural chemistry of simple inorganic substances, inorganic complexes, organic substances, the silicate minerals, and metals and intermetallic compounds. The development of molecular spectroscopy, especially during the period 1918–1925, has also led to the acquisition of much structural information. Perhaps the most important experimental technique for the investigation of the molecular structure of organic substances has been the electron diffraction technique, developed in 1929 by H. Mark and R. Wierl, which has been used in the determination of interatomic distances and bond angles for many hundreds of organic gas molecules. The study of the electric and magnetic properties of substances has also been of value in the development of modern structural chemistry, and in recent years the methods of microwave spectroscopy have provided precise structural information for many rather simple molecules.

I myself remember well the exciting second period of progress in quantum theory, which occurred during the twenties. One after another, experimental facts were found to show a small or large incompatibility with the old quantum theory; in many cases a patched-up reconciliation was brought about by means of *ad hoc* changes, such as the use of half-integral quantum numbers; and finally the great clarification was achieved, through quantum mechanics and the spinning electron. The observed small difference in vapor pressure of isotopes in condensed isotope mixtures was recognized by O. Stern in 1919 as requiring zero-point oscillational energy, and this conclusion was soon verified by the isotope effect in the vibrational spectra of diatomic molecules. The pure rotation spectra of the hydrogen halides were found to require a change in the representation of quantized energy levels. Millikan and Bowen emphasized the anomaly in the explanation of two kinds of x-ray and optical doublets in terms of the same differences in the ellipticity of the Bohr-Sommerfeld orbits. The magnetic and electrical properties of dipolar gases were found to differ from those predicted by the old quantum theory. And no postulates about half-integral or otherwise abnormal quantum numbers could be devised that would permit the old quantum theory to be brought into quantitative accord with the known energies of formation of the helium atom and the hydrogen molecule-ion (a structure containing the simplest of chemical bonds). The old quantum theory, with its suggestion of two types of electronic orbitals, including either one or two atomic nuclei, seemed not to be compatible with the chemical evidence for a con-

tinuous sequence of chemical bonds, from the ionic extreme to the covalent extreme; and, indeed, the differences between the chemists' atom and the physicists' atom seemed to be so great as to make their synthesis inconceivable. Then the new quantum mechanics was discovered, and within a few years all of these problems were solved.

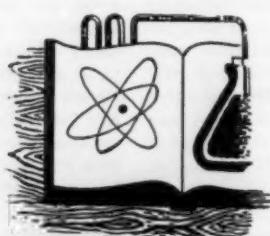
The discovery of the wave character of electrons by L. de Broglie, Davisson and Germer, and G. P. Thomson, and the development of quantum mechanics by Heisenberg, Schrödinger, and Dirac, initiated the second period of rapid progress in the process of conversion of theoretical chemistry into its present state. The Pauli exclusion principle, with its quantum mechanical explanation in terms of antisymmetric wave functions and the spinning electron, completed the fundamental theory of the periodic system of the elements in terms of electronic structure. The shared-electron-pair chemical bond postulated by G. N. Lewis was found to have a sound basis in quantum theory; Büräu, Heitler and London, Slater, Mulliken, Hund, Hückel, and many other people contributed to this development. In the period of a few years beginning in 1930 other aspects of the general theory of the electronic structure of substances were formulated, including the hybridization of bond orbitals and the resonance of molecules among two or more structures of the valence-bond type. The theory of the rates and mechanisms of chemical reactions was also brought into its present state. After early work had been done by R. C. Tolman, O. K. Rice, L. S. Kassel, H. Ramsperger, G. N. Lewis, and other workers (with the closely related problem of radioactive decomposition of nuclei treated by Condon and Shortley, Gamow, Born, and others), the theory was brought into its present form by F. London, Polanyi, Eyring, and Hinshelwood, and, in its application to organic reactions especially, by Ingold and F. O. Rice.

Another outstanding step in the development of an understanding of nature was the discovery of the explanation of van der Waals forces of attraction, by F. London, in 1929, as resulting from the mutual polarization of atoms through synchronization of their electronic motions. Important also was the formulation

of the electronic theory of metals by Pauli, in his treatment of the weak temperature-independent paramagnetism of the alkali metals in 1926, and its extension by Sommerfeld, Eckart, Houston, Mott, and many other workers. Although the part played by the quantum theory in their discovery is an indirect one, the many new elements that have been manufactured in recent years must also be mentioned in a review of chemistry during the twentieth century; it cannot be denied that the neutron and the transuranium elements are to be considered as a part of quantum chemistry, rather than of classical chemistry.

Thus we have reached the fiftieth anniversary of the discovery of the quantum of action, with the science of chemistry largely clarified as a result of this discovery. There are still problems to be solved, and some of them are great problems—an example is the problem of the detailed nature of catalytic activity. We can feel sure, however, that this problem will in the course of time be solved in terms of quantum theory as it now exists: there seems to be little reason to believe that some fundamental new principle remains to be discovered in order that catalysis be explained.

We may now ask about the puzzling problems in the other dimensional regions, in relation to quantum theory. It is clear that in the field of the elementary particles, their interaction with radiation, and their aggregation into nuclei—that is, in the dimensional region around  $10^{-12}$  cm—significant changes in the present quantum theory remain to be made. On the other hand, I believe that in the region of the gene, the dimensional region around  $10^{-8}$  cm, there are comprised only structures and reactions that can be interpreted in terms of the present system of chemical and physical theory, and that no fundamental new principles need to be applied. The problem of the gene and of biological phenomena in general will be solved, I believe, when more structural information about biological systems has been gathered. As to the dimensional region of universes,  $10^{24}$  cm, I do not know: I do not know whether or not we have reason to anticipate the discovery of a megasscopic quantum theory of the universe, but such a possibility should not be ruled out of consideration.



# Conceptual Foundations of the Quantum Theory

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## THE WORLD OF CLASSICAL PHYSICS

**F**IIFTY YEARS AGO, when Planck discovered that light is not a continuous wave but a series of energy pulses, the world of science was amazed. Incredulous and perplexed at first, it hesitated to accept so strange a notion as the "quantum" but was forced nevertheless to acknowledge it as viable and healthy. Thus Planck's famous *h* survived its first few years as a curiosity and as a misfit, while most physicists tried to isolate it as far as possible from the more acceptable ideas that formed their stock in trade. Its originator himself, who may be quoted here, "tried immediately to weld the elementary quantum of action *h* somehow into the framework of the classical theory. But in the face of all such attempts, this constant showed itself obdurate. . . ." "Many of my colleagues," he goes on to say, "saw in this something bordering on tragedy" (M. Planck, *Scientific Autobiography*, New York: Philosophical Library [1949]).

Discovered as an exception to all rules, the quantum effect developed during the following two decades into a major threat to the long-cherished idea of continuity. Einstein's explanation of the photoelectric effect (1905) and Bohr's atomic theory (1913) exposed the workings of quantization in a far wider range than had been assumed originally, and the question arose whether all fundamental processes of nature might not take place discontinuously. Light energy, it was learned, was transmitted in pulses called photons; electrons jumped suddenly and unpredictably from atomic orbit to atomic orbit; molecules vibrated in discrete states of motion. Might it not be, then, that all phenomena ultimately partake of such fitfulness, that everything comes in lumps of smallest but finite size, that continuity is a myth?

These were among the most radical questions asked up to 1925. They reflect a readiness on the part of science to abandon some of the traditional ideas about the qualities of the universe and to replace them by features that seemed strange at the time; but the spirit behind the inquiry was still the desire to learn new things about a world of preconceived essences. Science at this time would grant the possibility of unexpected features, such as discontinuity, but would not doubt the basic methodological premises on which our whole conception of the world is based. It did not question complete objectivity of description, the

independence of the known from the knower, nor did it cease to think in terms of mechanical models, nor doubt the predetermination of physical events. All these unorthodox doubts have been raised and confirmed in the past twenty-five years. They were precipitated by the remarkable series of incisive discoveries connected with the names of Bohr, Heisenberg, Schrödinger, Dirac, Born, Jordan, Compton, de Broglie, and many others.

Today, many scientists still think of the quantum theory as the doctrine of discontinuity, according to which all ultimate parts and properties of nature have some smallest measure. But it is in fact far more than this: a new way of thinking, a new view of physical reality, a new interpretation of the relation between the observer and the world. The sense in which this is true will be outlined in the following pages.

It is against the backdrop of "classical physics" that these profound changes have taken place, it behooves us to portray the backdrop first. The reader will find in this portrayal a statement of some of his firmest convictions, a summary of the scientific creed of centuries, indeed the gist of what he would regard as common sense. Only on realizing this does the magnitude of the departure that the quantum theory represents become apparent.

Our description of classical physics will concern itself with only one part of this wide field, the part called *classical*, or *Newtonian*, *mechanics*, which is at once its simplest chapter and the most typical representative of its procedures. It is a lineal descendant of astronomy and has inherited the grandeur, as well as the inexorability, of that ancient branch of science. Kant, whose philosophy can be called the metaphysical distillate of Newtonian mechanics, classed the starry heavens with the human conscience as the two deepest sources of our knowledge and our attitudes.

The motion of the stars is impressively continuous. They occupy every point of their path. The slowness of their motion accentuates its continuity. Clouds often obscure the stars, thus seeming to destroy their steady course. Yet this very interference and the ease with which it can be explained away by reference to the vagaries of the weather make the fact of continuity all the more sure and convincing.

Add to this the well-known circumstances that the path of a heavenly body has a mathematically simple form. Such simplicity is impaired if any points or

pieces are missing from the mathematically perfect orbit, and in the same way, a star's motion can hardly sustain the blemish of having blind phases or of being jerky. Thus continuity, certified within limits by vision and supported by maxims of simplicity and perfection, is one of the clearest attributes of celestial motions.

Once the pattern is set, the scientist experiences little difficulty in comparing it with the more ordinary motions of his daily life. Analysis, a little more reliance on the essential simplicity and perfection of the world, restores harmony with the cosmos and re-establishes continuity as a ruling principle of science. Only atomic physics was able to impugn it.

But continuity is only one facet of a more general supposition about nature, which is espoused in its totality by classical mechanics. The stars have attributes besides position and speed of motion; they exhibit brightness and color as well. Continuity is assigned to all of these, and the whole complex of phenomena named a star is expected to behave in a manner we might call *consistent*. On the lower plane of everyday experiences, consistency comes to mean continuity of an ever-widening set of properties, such as size, shape, temperature, energy content, and indeed all the refined attributes with which physical science endows its systems. And, beyond this, consistency requires an interrelation between all of these; hence the inexorability which the human interpreter once saw in the stars is implanted into lesser nature as determinism or causality.

Another aspect has been borrowed from the celestial bodies and invested in classical mechanics generally. It is the aloofness of the stars, their inaccessibility to designed experimentation. Human actions have no effect on them, their fate is independent of man's. To be sure, this stringent kind of independence cannot be carried into objects that the experimenter can manipulate, for he is clearly able to make them do some things they would not do without him. The classical physicist therefore lessens the rigor of celestial motions by advancing the notion of *interaction*. He supposes that object A can influence object B in a precisely determinable way, precise in the sense that he is always able to specify which is object A, which is object B, and which is the interaction. In this way, although he admits of interaction between the observer and what is being observed, he nevertheless retains the essential features of the grand conviction that "here am I," and "over there is the universe." These two are separate entities, engaged in the drama of being, which presents itself under the forms of a spectator and a spectacle. This spectator-spectacle distinction, generated by the early contemplation of the heavens, has continued to be a hall mark of classical mechanics and has characterized all thinking up to 1925. Its renunciation is still regarded as anathema by most scientists and many philosophers. The reason for this stand is a belief that the spectatorial doctrine is the only one that achieves objectivity and insures

reliability of report. We now know from an analysis of Heisenberg's uncertainty principle that there are other ways of representing our experience which do not fall short of these desiderata.

It is well to pause and see more concretely what these vaguely worded conceptual premises of classical physics are. For contrast, then, I shall describe the kind of experience that would belie these premises and then raise some questions that might seem natural if such experience were encountered. Imagine the star, while being observed, to behave very much as it does in our world, remaining stationary or slowly moving so long as our eye or the telescope is trained on it. But assume that, when we turn our gaze away and then look again, the star has altered its position, only to behave regularly again while under observation. Certainly, this does not happen among the stars in our world but is conceivable and not contrary to any laws of thought. If it did happen, would we still say without qualification, "the star has position," "its motion is continuous," "the fate of the star is independent of the observer," and would we still maintain the spectatorial doctrine?

Or suppose an object had the ability to outdo a chameleon and change its color erratically on different occasions of observation. Would we then still assign to the object a color, although this color is highly indefinite? If our super-chameleon displayed a different color everytime we looked but retained it while our gaze is fixed upon it, would we regard ourselves as mere spectators or feel in some way responsible for the grotesque emergence of differences? Again, the physicist is not confronted with this situation and is likely to smile at the naivete of such questions.

But there are fields of experience in which similar questions make sense and are answered. Take an example from psychology. People have at times the quality of being angry. If they possess sufficient self-control, a direct observation may not yield a clue to their anger, and a verbal inquiry may be necessary to ascertain it. The results of inquiries at different times are quite likely to be erratic, and it is certainly not a foregone conclusion that the subject's states of mind are independent of the fact that an inquiry has been conducted. The social and biological sciences abound with similar examples, where the spectator-spectacle view becomes artificial and can be maintained only by an appeal to classical physics, made in the hope that this discipline will prove successful where it has not been tested.

If we take the facts of our simple tests on a person's anger without embellishment, we find, in the first place, that he is sometimes angry and sometimes not. We would therefore not speak of anger as a property which a man always possesses, but one which he *may* exhibit. In the physical world, objects are assumed to have certain properties (like position and size of stars), which they *must* possess at all times. Galileo spoke of them as primary qualities and distinguished them from secondary qualities that arise

in the act of perception (e.g., color). Nowadays this distinction is difficult to maintain, chiefly because it is impossible in many instances to prove that a quality owes its occurrence to the perceptory process. Still, there is a difference between a quality that is merely a *latent* or possible attribute, and the position of a physical object, which is assumed to be inalienably *possessed* though its value may change. Thus, for the sake of fixing attention, let us speak of possessed properties when referring to such determinate and intuitively objective qualities as the position of a tree, the mass of a stone, the velocity of an automobile, on the one hand; of latent properties when referring to such transient qualities as the anger of a person, the value of a commodity, and (perhaps) the life of a virus, on the other.

In this language, classical mechanics may be characterized by saying that it regards all properties it uses in the description of experience primarily as possessed by objects. What was called continuity, consistency, independence, is seen to be included in this generalization. Sensory experience, as it explores our far and near surroundings, justifies the point of view of classical mechanics.

#### THE MICROCOSM

Classical mechanics has largely come to be identified with common sense. As we transport ourselves to the world of atomic magnitudes, which we now propose to do, we shall seem in some measure to be violating common sense. Hence there is need to indicate at once on what grounds we are entitled to abandon this time-tested criterion of truth. And here it may come as a shock to the reader to be told that so-called common sense has never had a shred of validity in the face of new and revolutionary theories of nature. The latter have ever had to assert themselves in the face of reactionary beliefs parading under that guise, and when these new theories succeeded, common sense readily adjusted itself to include them, as it should; for this overruled principle of truth is nothing more than the popular residue of accepted scientific theories and embodies their familiar features. It never leads, it always follows, scientific discovery. D'Alembert unmasked it in his motto for the scientists: "*Allez en avant, la foi vous viendra.*"

To survey the facts of the microcosm—i.e., the observations that have led to the construction of the quantum theories in their present form—we assume our sense organs to be replaced by more sensitive devices, such as the electronics expert can actually build, devices which allow us to perceive very small distances, very short intervals of time, and extremely light objects. Although somewhat idealized, this assumption is not pure fiction; nor is such apparatus a fanciful dream. The fact that devices of this kind have actually been built and used saves our story from being imaginary and makes it relevant.

In this atomic world we perceive no coherent objects. Our "eyes" are now sensitive to the single darts

of light (photons) cast off by single luminous atoms. Hence our microcosm is not uniformly illuminated and filled with moving things; it presents a speckled kind of vision with bright patches emerging here and there from utter darkness, different patches having different durations. Distant objects of large size and mass exhibit a kind of uniform glow and suggest some cohesion in this chaotic scheme of things, but the smaller dots near by give very little indication of uniformity or pattern.

An unimaginative observer restricted to this world would hardly postulate persistent bodies present at all times; he might indeed doubt the existence of entities except at the moment of vision. He would not find it plausible to speak of the flow of time, regarding "emergence of sensed intervals" as a more satisfactory phrase. To him, continuous space might seem a farfetched abstraction, and if he were to postulate the presence of objects, he would hardly suppose them to have definite positions at all instants of time. Certainly, he would have little occasion to invent the differential calculus.

On closer examination the microcosm reveals some degree of coordination. Patches of light are not completely random but appear in more or less ordered sequences. There are times when nothing can be seen, and then again the visual field is dotted with perceptions. Furthermore, these perceptions often indicate a preferred location in space—though they rarely mark a point. The physicist who knows about the microcosm, when noting this modicum of regularity, will of course take it as the occasion for postulating the existence of objects, vaguely localizable in space and somehow progressing from one place to another; his instinct for causation is thus satisfied. But if he had never seen a perfectly continuous path he would hardly regard them as moving in our sense—position and velocity would doubtless be what I have previously called *latent properties* of an object. He would encounter as much difficulty in the idea of continuous motion as we ordinarily do in the notion of discontinuous emergence in our world.

Properties of objects are like anger of a person in another respect. Our microcosmic observer will see things under two conditions only: Either he illuminates them by means of an external light source, or he waits for them to emit photons. In either case will their manifestations be random. (To be sure, there are possibilities for "tying down" an atom by letting it move in a very small space in a most erratic manner—but such cases are the exception and not the rule.) The macroscopic physicist feels uneasy about this, and he advances the none-too-ingenuous conjecture that he, himself, or incidental circumstances, are to blame for the randomness. When things are illuminated, he reasons, they are being bombarded by photons, and their impacts are the random cause of lawless appearances. When atoms are self-luminous, recoils from ejected photons propel the emitters about in unpredictable fashion. But how is he going to tell? No observation

is possible without the agencies of external or self-illumination; a control experiment is out of the question. The psychologist can at least ask a subject, "Are you angry because I am asking you this question?" The physicist can ask his atom only, "Are you angry?" Despite all this, it does no harm if the physicist tries to explain the erratic behavior of the atomic world by a reference to causative agencies; it affords him comfort and makes the microcosm seem less strange. The fact is, however, that he is then indulging in a bit of metaphysical speculation, and he ought to be aware of it.

Closer study of phenomena discloses order imposed on randomness even in the Lilliputian world. The mean positions of what was construed as objects seem to obey definite laws. That is to say, if a list were made of the appearances in space of a group of luminous dots, and their mean were computed in the manner by which one obtains the center of a population, this center would move more or less in accordance with macroscopic laws. In fact, nature often relieves us of the need for this computation by doing it herself. We have already said that the more distant objects of the microcosm show coherence and a measure of consistency. This is because they are made up of many atoms and large masses, which consolidate their moods into relative certainties.

It is a long journey from the atomic to the celestial sphere, from apparent caprice to the majestic imperturbability of the stars. And yet one can pass from one to the other without changing one's philosophical equipment. The statistical regularity, which we noted in the microcosm and which is entirely compatible with individual randomness, can condense itself to practical lawfulness in the domain of large and heavy objects, just as a probability can tend to the limiting value one. This is indeed what happens: Newtonian (classical) mechanics can be shown to be the "limiting form" of quantum mechanics. The universe is therefore still of one piece. Note, however, that the story is not reasonable when told the other way around. Quantum theory is not a limiting form of classical physics, for it cannot be readily conceived how mechanical lawfulness could degenerate into statistical behavior, unless the latter had been embryonically present at the start: Statistical regularity is the more general concept and must be regarded as primary. This confers upon the quantum theory the status of logical priority over classical mechanics and over common sense.

Summarizing, we may say that sensorylike experience in the microcosm lays bare the precariousness of assuming physical properties, like positions and velocities, to be necessarily and at all times possessed by physical systems. They may become latent observables.<sup>1</sup> In particular, continuity and consistency are not suitable attributes of individual atomic behavior.

<sup>1</sup> The word *observable*, introduced by Dirac, has come to mean any physical property which can be observed or measured.

## REPRESENTATION OF EXPERIENCE IN CLASSICAL MECHANICS

The conceptual tools used by the physicist must be in accord with the nature of the experience he wishes to represent. In view of the regularity of stars and stones and all the other objects of the macro-world he must employ a very determinate kind of description, which I shall briefly illustrate. The simplest object, or physical system, is a *particle*, and complex bodies are assumed to be composed of particles. A particle has a definite mass and is assumed to occupy a definite point of space at every instant of time. The *state* of a particle—by this we mean a collection of attributes or properties, all possessed in the present instance, which are just sufficient to allow prediction of future behavior—is given when a position and a velocity (or, better, momentum) are specified. Since these are functions of the time, both must be allowed to vary. All this leads quite naturally to one result: position and velocity are *functions* of time, since a function is that mathematical construct which can be made to vary continuously and then carries exact values for all values of its argument.

By the same token, all other "observables," such as energy, angular momentum, etc., are regarded as functions of the time, either directly or indirectly through their dependence on position and velocity. To use an earlier terminology, they are invariably possessed observables, having a meaning independent of observation at all times. States, in this classical scheme of things, are causally related in the following way. There are available laws of motion, which are differential equations of such character that their solutions are made definite by constants of integration, which are precisely the quantities employed to define a state. In the case of a particle, position and momentum,  $x$  and  $p$ , determine a state. Newton's second law regulates the motion. It can be integrated to yield  $x$  and  $p$ , but the integral will be indefinite. When  $x_1$  and  $p_1$ , values at some specific time, are given,  $x$  and  $p$  become determinate and prescribe the motion for all times. Thus the state,  $x_1$  and  $p_1$ , of the system at time  $t_1$  is the "cause" of all later states.

One characteristic feature of this formalism is its rigid link-up with observation. A state specifies one possible position and one possible momentum; conversely, a single measurement of each of these observables performed upon a system suffices to determine its state. There is a unique correspondence between a "state variable" and an individual measurement of it; actually this is a typical feature introduced by the tacit use of possessed observables. Somehow, our whole notion of physical reality is colored by this fortunate appearance of a unique correspondence between simple acts of perception and significant theoretical description. Yet the quantum theorist must recognize the limitations of this view in order to keep the prospects of future theoretical developments unencumbered.

We have now seen how naturally our large-scale experience can be comprised under such maxims as these: Physical things consist of particles. Particles have certain determinate properties at all times. Their states are suitable collections of observable quantities, and such observables are represented by mathematical functions. Each observable can in principle be measured through a single act of observation.

The mathematician might wish to express the classical situation by speaking of a simple *isomorphism* between our description of nature and our immediate experience.

#### REPRESENTATION OF EXPERIENCE IN THE MICROSCOSM

Clearly, so straightforward a scheme will not work in the erratic world of the atom, and physicists have found it necessary to adopt a less familiar formalism. To say that the new theory is less simple is hardly fair, for simplicity is largely a matter of taste and prior conditioning. Let us see what requirements the new formalism ought to satisfy.

We still wish to populate the world of space and time with objects or, to use a more neutral phrase, with physical systems. It goes without saying that these need not be of the material variety (e.g., electromagnetic fields)—need not, in fact, even carry energy (e.g., the sinusoidal component of a group of waves). But a physical system is still the carrier of observables. On the other hand, these observables are not necessarily of the possessed variety, may not have values under all conditions and at all times. Continuous functions are therefore *not* their natural representatives. Yet the observables must provide a link with measurements—though perhaps not a unique link, since measurements are known to scatter—and measurements yield numbers. Consequently, whatever the representative of an observable turns out to be, it must provide numbers to be checked against observations. Whether the state of a physical system may continue to be a collection of observables as it was in classical mechanics, will have to be decided by the available mathematical opportunities; there is, at any rate, no logical requirement that this must be the case.

By the bounty of providence, there is not one, there are at least three formalisms that satisfy the requirements just cited. The matrix theory advanced by Heisenberg, the operator calculus discovered by Schrödinger and perfected by Dirac and Born, the theory of vectors in Hilbert space proposed by von Neumann, are equally satisfactory from most points of view and lead to the same verifiable results. It is therefore superfluous to describe them all, and I shall limit my account to what is essentially the Schrödinger-Dirac-Born method, restricting it further, of course, to conceptual structure without detail.

Rather central in this quantum mechanical scheme of things is the notion of a *mathematical operator*. Though the word sounds forbidding, it signifies some-

thing very simple indeed. Let  $f(x)$  be some function of the variable  $x$ , such as  $ax + b$ , or  $\sin x$ . To operate on  $f(x)$  means to change it into some other function, say,  $g(x)$ ; hence anything that changes  $f(x)$  is called an operator. Multiplication by  $x$ , which changes  $ax + b$  into  $ax^2 + bx$ , is an operation; and the symbol  $\times x$  that represents it is an operator. So are the integral sign and the symbol for differentiation. It is customary to write a capital letter for an operator. Thus, if  $Q$  stands for  $\frac{d}{dx}$ , and  $f(x) = \sin x$ , the equation

$$\frac{d}{dx}(\sin x) = \cos x \text{ may be written}$$

$$Qf(x) = g(x), \quad (1)$$

$g(x)$  being the new function  $\cos x$ . Almost any operation can be written in this form, which has the advantage of displaying the mathematical elements that are important here: the *operator*  $Q$ , the *operand*  $f$ , and the *result*  $g$ . The choice of operators in mathematics is, of course, extremely large.

Many of them have this rather interesting property: When applied to *certain* functions, they will simply multiply them by a constant factor. Thus the operator  $\frac{d^2}{dx^2}$  when applied to  $\sin x$  or to  $\cos x$ , merely changes the sign of the function; i.e., multiplies it by  $-1$ . A function  $F(x)$  which is "immune" to an operator  $Q$  (i.e., is only multiplied by a constant when acted on by  $Q$ ) is called an *eigenfunction* of  $Q$ . In symbols,

$$QF(x) = qF(x). \quad (2)$$

The constant  $q$  is said to be an *eigenvalue* of the operator  $Q$ .

Suppose that an operator  $Q$  is given. We can then write down its eigenvalue equation (2) and find the function  $F(x)$  and the corresponding  $q$ . But it turns out that there are, in general, many different  $F$ 's, each with its own eigenvalue  $q$ , for which equation (2) has satisfactory<sup>2</sup> solutions. Hence we may say that a mathematical operator  $Q$  "generates" a set of eigenfunctions  $F$  and a set of eigenvalues  $q$ . A specific  $q$  may belong to several  $F$ 's, but there are in general innumerable  $q$ 's for every  $Q$ .

TABLE 1

	Classical mechanics	Quantum mechanics
Observables	$x(t), p(t), \dots$	$Q, P, \dots$
State	$\{x, p\}$	$f(x, t)$
Observed values	Values of $x, p, \dots$ at different times	Eigenvalues of $Q, P, \dots$

After these preliminaries we are ready to state the basic ideas of quantum mechanics in reasonably precise form. Reference is made to Table 1 which

<sup>2</sup> That is, solutions satisfying physical conditions.

contains the nucleus of the following discussion. The column labeled classical mechanics presents a summary of what was said in the preceding section. Position  $x$  and momentum  $p$  are typical observables of a particle; its state is defined when  $x$  and  $p$  are known; and the values of  $x$  and  $p$  revealed in measurements are the values which the observables possess at the time  $t$  in question. This last remark will seem trivial to a person who fails to distinguish between possessed and latent properties.

In quantum mechanics an observable is represented by a mathematical operator  $Q$ , or  $P$ . (We use capital letters for operators.) An operator does not possess numerical values and cannot be measured. But latently it contains numbers, for it can generate them by means of equation (2). And here occurs the miracle of quantization: The discrete values of energy, action, light quanta, and so forth, discovered at the beginning of the century, all happen to be eigenvalues of certain operators! Quantization may indeed be considered a by-product of the indirect description of nature in terms of operators; the roots of quantization lie deeper, therefore, than the mere incidence of discontinuities in the physical world suggests.

The operators themselves have to be found by trial and error, although classical mechanics gives some valuable clues. The business of the theoretical physicist has therefore changed its scope. Whereas he previously sought for functions (such as  $\frac{1}{2}mv^2$  = kinetic energy) to represent his observables, he now searches for operators with suitable eigenvalues. (It should be noted, however, that a function is a specific form of an operator.)

The top and bottom entries in the last column of Table 1 are now explained, but the row labeled "State" is still mysterious. Since operators, and hence observables, do not in general "have" values, a unique collection of observed values cannot define a state in quantum theory. Here the greatest departure from classical physics is made. A state is represented by a function of the coordinates and the time,  $f(x, t)$ .

But what does a function,  $f(x, t)$ , have to do with the state of a particle? It certainly means nothing with respect to the behavior of a point moving continuously along a path. Let us remember, however, the idiosyncrasies of the microcosm, which did not contain such uniformly moving points. It presented erratic appearances of "luminous patches," held together by *statistical* coordination. The state function  $f(x, t)$  represents this statistical coordination. It tells, in fact, what the probability is that our system shall emerge at the place designated by  $x$  at the time  $t$ . Hence it conveys fully all the significant elements of our sensory experience in the microcosm; it provides the maximum of available information. When  $f(x, t)$  is given, the physicist can compute the *probabilities* for all events (observations) of which he can possibly become aware; but he cannot predict exactly *what* will happen. Indeed, if the present form of the

quantum theory is correct—and its immense success leaves little doubt as to its essential truth—precise prediction of all individual events in the microcosm is forever impossible.

#### UNCERTAINTY

The preceding developments raise important philosophic questions. Very little space can be devoted to them here. We have said that evidence for the persistence of objects in the atomic world is decidedly less obvious than in ordinary experience. Nevertheless, it is our habit to ascribe even the fitful and transient occurrences in the microcosm to the existence of enduring objects. In a sense, we postulate fireflies. And this practice is wholly above reproach, for it has never led us astray. But can we attribute the usual macroscopic qualities to microcosmic objects?

Clearly, it would be nonsense to speak of the color of an electron, since the electron is smaller than a wavelength of visible light. Equally precarious is the assignment of definite size and shape to this physical entity, because there are no unique experimental or theoretical procedures for ascertaining size and shape of such an object. But many of us hesitate to say the same about the electron's position. Yet it appears from every angle that position, too, has become a latent observable in its relevance to atomic entities, and we must not say that an electron *has* position at all times. The discoveries of quantum mechanics have forced us to become suspicious of the indiscriminate way in which the classical physicist assigned intuitable attributes to all parts of his domain. His trust in mechanical models now appears misplaced. Perhaps God is a mathematician and favors mathematical models.

Is the electron a particle or a wave? The vantage point we have now reached permits us to wonder idly why it should be either. If our knowledge of a firefly were confined to its spasmodic emissions of light, if we could not grasp and feel and handle it, we might not wish to speculate or pronounce judgment upon its mechanistic essence. It would remain an object of physical interest, describable in terms of what we know about it, both empirically and by the agency of valid theory. In the case of the firefly the assumption that it be corpuscular would in fact be a fruitful one; above all, it would never lead to contradiction with experience. In the case of an electron this assumption does lead to contradiction. So does the allegation that it be a wave. Hence it is simply neither. Nor is this a logical paradox, for wave and particle are not even exhaustive mechanical alternatives, let alone the only possible forms of physical reality. One of the lessons of quantum mechanics is its reminder that mathematical models are as good as mechanical ones.

This, then, seems to be the resolution of the wave-particle dualism which perturbed the adolescence of the quantum theory. Yet it is no mere historical accident that the ideas of wave and particle played

prominent roles in the development of the new formalism. For an electron (or any other so-called particle) the state function  $f(x, t)$  takes two important limiting forms. One implies absolute ignorance of the electron's velocity. The function  $f(x, t)$  is then completely localized; a single electron is certain to be found at some specific point of space and thus displays the crucial characteristic of a classical particle. The other limiting form implies absolute ignorance of the electron's position. Strangely enough,  $f(x, t)$  then represents a sinusoidal wave. This circumstance accounts for de Broglie's great discovery and for the name "wave mechanics," which is often applied to the new quantum theory.

Heisenberg's famous uncertainty principle comes within the present context. The two extreme situations just mentioned illustrate it. For one case there was perfect knowledge of position and complete ignorance of momentum; for the other, the converse. Generally, gain in the knowledge of position may be shown to entail loss in the knowledge of momentum. To be specific, the product of the uncertainties, when ex-

pressed in suitable units, is of the order of the magnitude of Planck's constant but never smaller than  $\hbar$ . This uncertainty relation springs directly from the use of operators to represent observables and therefore has its origin in the basic methodology of quantum theory.

Bohr's principle of complementarity is another interesting formulation of the same state of affairs. He holds that nature can be described in two complementary ways: (a) in terms of objects moving in space and time, this being essentially the method of classical physics; (b) in terms of the wave functions of quantum mechanics. One can never be wholly reduced to the other, and Bohr seems to regard both as necessary (complementing each other), for a complete description of experience.

Whatever view one wishes to take of quantum mechanical uncertainty, pessimism should be no part of it. Far from renouncing its hold on nature, the new theory grips nature all the more firmly while relinquishing its attachment in places that have become insecure.



## Technical Papers

### Nuclear Models

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Since there exists no exact theory of nuclear structure, one is forced to introduce a number of oversimplified nuclear models in order to explain the main features of the experimental material. The models can be classified into two distinct groups according to their fundamental viewpoints: (a) the independent particle viewpoint (I.P.); (b) the strong interaction viewpoint (S.I.).

Recently the I.P. models have been widely discussed in connection with the surprisingly successful application of shell structure to nuclear properties (1). One has observed abnormally large binding energies for nuclei for which either the neutron number or the proton number is equal to a series of so-called magic numbers. This phenomenon was interpreted by many authors by assuming that the nucleons move independently within a common potential trough. The energy levels in this trough are grouped in shells that are completely filled with particles (closed) when a "magic" number is reached. Very simple and general assumptions (e.g., spin orbit coupling) are sufficient to explain the observed values of the magic numbers. The physical properties of the different shells allow the prediction of more specific nuclear data, such as

the occurrence of isomers, the spins and, in some cases, the magnetic moments and the quadrupole moments of nuclei in their ground states.

It must be emphasized that this picture is based upon a far-reaching assumption: The nucleons must be able to perform several revolutions on their orbits before they are disturbed and scattered by the interaction with neighbors. This condition is necessary for the existence of a well-defined energy and angular momentum in each separate orbit. The "mean free path" within nuclear matter must be of the order of several nuclear radii in order to justify the existence of separately quantized independent states for each particle.

The S.I. models are based upon the opposite assumption. They are all derived from the concept of the Compound nucleus. Bohr (2) has pointed out that, in most nuclear reactions, the incident particle, after entering the target nucleus, shares its energy quickly with all other constituents. This picture presupposes a mean free path of a nucleon that is much shorter than the nuclear radius. Nevertheless the Compound nucleus picture is very successful in accounting for the most important features of nuclear reactions. To mention a few examples: The existence of closely spaced and narrow resonances in slow neutron reactions (2), the success of the evaporation picture of nuclear reactions with fast particles (3), the large values ( $\sim \pi R^2$ ) of reaction cross sections with fast neutrons (4).

The two viewpoints seem to be totally contradictory.

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The nuclear forces as we know them from the deuteron and from two-particle scattering experiments represent a strong interaction and therefore suggest the validity of the S.I. viewpoint. In fact, the known scattering cross sections of elementary particles at 20–30 mev (this is the order of the kinetic energy inside a nucleus) would indicate a mean free path of only  $10^{-18}$  cm with nuclear matter. Hence the recent success of the I.P. shell model has led to speculations that envisage much weaker nuclear forces within a nucleus, compared to the ones observed between isolated pairs.

It is the purpose of this note to point out that the I.P. and the S.I. models are perhaps not as contradictory as it appears at first thought. It must be noted that the successful predictions of the shell model are always applied to the ground states or to the lowest excited states of nuclei. The regularities in the binding energies are properties of the ground state, the spin, and the magnetic and electric moments, too. The occurrence of isomers is a problem of the first excited state. Even the small neutron capture cross sections of "magic" nuclei (5) can be interpreted by assuming that the ground state of the target nucleus has an unusually low energy. Then the captured neutron forms a compound nucleus of an abnormally low excitation and its level density will also be abnormally low. This leads directly to a low capture cross section, since the neutron width is then much larger than the radiation width.

The applications of the S.I. models are restricted to problems involving high nuclear excitation. The compound nucleus formed in a nuclear reaction is always excited, at least to an energy larger than the binding energy of the added nuclear particle (about 8 mev for protons or neutrons). Hence it seems that the strong interaction between nucleons within a nucleus is observed only at high nuclear excitations.

The failure of the S.I. viewpoint at low excitation energies does not necessarily imply that no strong interactions exist between nucleons. It is very probable that the Pauli principle prevents the strong interaction from exhibiting the expected effects. The interaction cannot produce the expected scattering within the nucleus, because all quantum states into which the nucleons could be scattered are occupied. Only at higher excitations, when not all of the lowest states are occupied, will scattering take place and prevent the formation of independent orbits.

It may be useful to discuss in this connection an analogous situation that one finds in the theory of the electron motion in solids. The electronic properties of metals and insulators can be described very successfully by assuming that the electrons move in a common potential field, the electric field of the ions in the lattice. The interaction between the electrons is completely neglected. The electronic states in the lattice field exhibit also a kind of shell structure, the Brillouin zones, and an insulator may be called a "magic" crystal for which the shells are completely filled.

The success of this description is perhaps also surprising in view of the fact that the interaction between electrons is by no means small. In fact, an electron with a few electron volts of energy that enters the metal from the outside is stopped in the metal within one or two interatomic distances, simply by the scattering with other metallic electrons. The mean free path of this electron within the metal is not greater than one interatomic distance, as can be shown with a simple calculation using the Rutherford scattering formula. In spite of this fact, the mean free path of the metallic electrons is very much greater than the interatomic distances; in fact, it is limited not at all by the interaction between the electrons but by the irregularities in the lattice. The reason is again found in the Pauli principle, which does not admit any scattering of electrons by electrons, because all states into which the scattering process may lead are occupied. This is not the case for the electron entering into the metal, since it possesses a surplus energy at least equal to the work function. Hence we find long mean free paths in the nonexcited state in spite of strong interaction, but short mean free paths in the highly excited state that is created when an electron enters from the outside.

The conditions of the electrons in a metal are obviously quite different from the conditions of the nucleons in a nucleus. There is no external field in the nucleus corresponding to the ionic field in the crystal. The common potential in the I.P. model is the average effect upon one single nucleon of all other constituents. However, the influence of the Pauli principle upon the mean free path of the electrons may serve as a useful analogy to understand the possibility of an I.P. picture in the presence of strong interaction between nucleons.

It should not be concluded from these considerations that the force between a pair of nucleons within a nucleus is necessarily equal to the force observed with an isolated pair. The failure to explain the saturation properties in heavy nuclei on the basis of the observed exchange character (Serber force) of the neutron-proton forces suggests a different character of the nuclear potential within the nucleus. The recent successes of the shell model, however, do not necessarily imply that the forces between nucleons within the nucleus are very weak. In fact, this assumption would contradict the experimental evidence of the validity of the S.I. model in nuclear reactions.

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## Regarding Covariant Subtraction of Infinities<sup>1</sup>

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It has been brought out by Pauli and Villars (1) that requirements of covariance are not sufficient to determine physical answers in the Tomonaga-Schwinger (2) formulation of quantum electrodynamics, and that the indefiniteness of the theory is caused by the indeterminateness of the four dimensional  $\Delta$ -functions. Pauli and Villars (1) show that by formal regularization the results may be changed within wide limits. A few remarks may be permitted concerning this feature of the theory.

1. There is a close relationship between the Dirac-Fock-Podolsky (3) formulation and the new one, as has been emphasized by Tomonaga (1). The new formalism differs from the DFP formulation mainly through the employment of quantized matter waves. In the DFP theory the supplementary condition has the form

$$[\text{div } \mathbf{A} + \partial\Phi/\partial t - \Sigma e_s \Delta(\mathbf{X} - \mathbf{X}_s)/4\pi] \psi = 0,$$

where  $\mathbf{A}$ ,  $\phi$  are the vector and scalar potentials,  $e_s$  are the charges,  $\mathbf{X}$  and  $\mathbf{X}_s$  designate respectively the four dimensional field and particle positions. The function  $\Delta$  is  $4\pi$  times Schwinger's  $D$ . It is well known that the above equation of constraint contains singularities, as is especially clear in its consequence

$$\{\text{div } \mathbf{E} + (\partial/\partial t) \Sigma (e_s/4\pi) \Delta(\mathbf{X} - \mathbf{X}_s)\} \psi = 0,$$

and the corresponding formulas for  $\partial\mathbf{E}/\partial t$ . The above comparison shows that one can hardly expect unique predictions without a precise specification of the averaging process employed in dealing with the  $\Delta$  or  $D$  functions.

2. The Pauli-Jordan invariant  $\Delta$  function has been extended by Dirac (4) so as to include cases with non-vanishing mass. Whereas Schwinger's (1) treatment is more symmetric regarding space-time, the explicit character of Dirac's work has advantages. One can verify, following Dirac's calculation, that for  $\lambda > 0$

$$\bar{\Delta} = [\delta(\lambda)/4\pi] - (\kappa_s^2/8\pi) J_1(\kappa_s \lambda^{1/2})/(\kappa_s \lambda^{1/2}),$$

where

$$\lambda = -r^2 + x_0^2,$$

in agreement with Schwinger. One has also

$$\bar{\Delta} = -(\partial/8\pi r \partial r) F(\kappa r, \kappa_s x_0),$$

where

$$F(\kappa r, \kappa_s x_0) = J_0(\kappa_s \lambda^{1/2}) (\lambda > 0)$$

$$= 0 (\lambda < 0).$$

<sup>1</sup> Assisted by the joint program of the AEC and the ONR.  
<sup>2</sup> The present note owes much to a verbal statement made by Professor Heisenberg to the effect that he believes that his new theory will give results similar to those of Schwinger and Feynman for large-scale phenomena. For this, as well as a generally stimulating discussion of the convergent theory, the writer would like to express his sincere thanks. Thanks are also due Professor Belinfante, who kindly pointed out some inconsistencies in notation in a preliminary form of this note.

The function  $F$  has a discontinuity on the light cone. The introduction of  $\Delta = -2(x_0/|x_0|)\bar{\Delta}$  removes the discontinuity in its surface integral, but the discontinuity of  $F$  remains.

A natural but nevertheless arbitrary way of removing the singularity is to consider the  $\delta$  functions in

$$(\square - \kappa_s^2) \bar{\Delta}(x) = -\delta(x_0) \delta(r),$$

as defined in the sense of being the limit of a family of nonsingular functions obtainable, e.g., by first Fourier-analyzing and then proceeding to the limit in the space of the wave number  $k/2\pi$  of this analysis by integrating from  $-N$  to  $+N$  and making  $N \rightarrow \infty$ .

3. Although, according to Pauli and Villars, one cannot claim that the Tomonaga-Schwinger attempt derives its results from general principles, it is also true that the intuitive methods of calculation agree with experiment. The addition of a hypothesis that invariant  $\Delta$  functions should be first replaced by a Fourier Integral, which should next be replaced by a similar integral with finite limits of integration (or infinite limits but with a weighting factor), is admittedly arbitrary. Such a procedure is closely related, however, to Heisenberg's convergent theory (5) of elementary particles, in which an elementary length is introduced in virtue of the elementary interaction. The commutation relations are here nonsingular, and the formulation adapts itself to a Fourier representation. One may expect, therefore, that for lengths large compared with Heisenberg's elementary length the consequences will be similar to those obtainable from the TSFD developments, with the addition of a postulate concerning the method of evaluation of divergent expressions along the lines carried out in Schwinger's papers. The weighting factor should then appear in an approximation neglecting phenomena within the elementary length. The symmetry in the treatment of the Fourier representations may be expected to arise through the virtual creation of other than the interacting particles. Since the creation takes place in the region of space-time containing the singularity of the TSFD discussions which corresponds, e.g., to  $\lambda = 0$  in equation (2.33) of Schwinger's second paper of the series quoted, the  $\Delta$  functions of the TSFD theory will be modified for large  $k$ . The writer believes, therefore, that future theories will agree in the limit of large lengths with the ( $k$ ) representation and its symmetric calculation.

The introduction of symmetry requirements for the magnetic moment problem occurs in Schwinger III in the evaluation of the logarithmically divergent integral occurring in equation (1.103) for  $n = 0$ . The invariant minimum light quantum number associated with the infrared catastrophe is introduced in his equation (1.107) and the Fourier representations in equation (1.66). The operation would be impossible without the physical identification made in equation (1.106). The related discussion in the Appendix is in terms of the  $k$  representation of the singular functions. In the discussion of vacuum polarization similar steps

occur in relation to equation (2.36) and (2.39) of *Schwinger II*.

It may be argued that ordinary space-time is as good as (*k*) space. But the occurrence of new particles appears more directly in the latter on account of the connection with energy and momentum. The effect is as though "elementary particles" had a size, as has been brought out by Heisenberg (5).

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### Nonclassical Reaction Kinetics

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Barrier leakage was early invoked by Gamow and by Condon and Gurney to explain nuclear decomposition. For particles of mass *m*, position *X*, and energy *E<sub>i</sub>* in the *i*th state, moving on a potential energy surface *V(X)*, the specific reaction velocity, *v*, (or frequency of passing a smooth energy barrier (*E<sub>i</sub>* < *V*)) which occupies the region (*X<sub>1</sub>* ≤ *X* ≤ *X<sub>2</sub>*)) may be written:

$$v = \sum_i n_i v_i \gamma_i = 4 \sum_i n_i v_i \exp \left( -\frac{2\sqrt{2m}}{\hbar} \int_{X_{1i}}^{X_{2i}} \sqrt{V(X) - E_i} dX \right), \quad (1)$$

where *n<sub>i</sub>*, *v<sub>i</sub>*, and *γ<sub>i</sub>* are the fractional population of the *i*th level, the frequency of vibration normal to the reaction barrier, and the probability of barrier penetration per encounter, respectively. Because of the flatness of barriers in ordinary chemical reactions, leakage is usually negligible in comparison to the surmounting of barriers. The inversion of the ammonia pyramid is one of a small group of interesting exceptions that are reasonably well understood.

Hardness, electrical resistivity, and magnetism of metals, when treated as rate processes, provide added examples of nonclassical kinetics. Application of the classical expression for the net specific rate *k'*<sub>net</sub> of surmounting barriers

$$k'_{\text{net}} = \frac{2\pi kT}{h} \exp \left( -\frac{\Delta F^{\ddagger}}{kT} \right) \sin 1 \cdot \frac{V \cdot \sigma}{2kT} \quad (2)$$

<sup>1</sup>The authors are indebted to ONR for support of this research activity. (Because the authors failed to receive proofs of this article before the issue went to press, any necessary corrections will be printed later.—Eds.)

to plastic flow of metals by Fredrickson and Eyring (1) and Kauzmann (2) led to a free energy of activation  $\Delta F^{\ddagger}$  proportional to the temperature (a pure entropy) and  $\frac{V_h}{2kT}$  independent of the temperature. *V<sub>h</sub>*, with the dimensions of volume, is the area of the slipping unit in the plane of slip times the mean distance traveled per slip. That *V<sub>h</sub>* should be proportional to the temperature is not impossible, but scarcely to be anticipated (3).

It seems more natural to replace the classical equation (2) for plastic flow by the appropriate extension (1), from which the observed temperature effect follows easily. In this case, the effective potential *V(X)* is reduced at each point along the barrier by a small amount *a<sub>σ</sub>*, against motion of the particles in the direction to relax the stress *σ*; and is raised by a similar amount against return to the initial state, once the barrier has been passed. This is to be understood in terms of the distortion of the average electrostatic field by a relative displacement of the mean positions of atomic kernels. Expanding the radical in equation (1) to the first order in powers of *a<sub>σ</sub>* (the correction to *V*) and replacing the sum by a single "average" term, we obtain for the excess velocity in the direction to relieve stress over that of return

$$v_{\text{net}} = 8\bar{v} \exp(-\bar{g}\bar{m}p) \sin h(\bar{b}\bar{m}p\sigma), \quad (3)$$

where

$$\bar{g} = \frac{2\sqrt{2m}}{\hbar} \int_{X_{1i}}^{X_{2i}} \sqrt{V - E_i} dX, \quad \bar{b} = \frac{|2m|}{\hbar} \int_{X_{1i}}^{X_{2i}} \frac{dX}{\sqrt{V - E_i}},$$

and *m̄* and *p̄* will be discussed shortly.

Equation (3) must be interpreted as follows: Crystal geometry permits slip only through the cooperation of *m̄* neighboring atoms. At moderate temperatures these atoms may be treated as independent oscillators, as in the Einstein theory of specific heats. *v̄* is the effective frequency of vibration of the normal mode along the slip plane. These electrons must each penetrate the electrostatic barriers separating initial and final configurations if slip is to occur. For independent atom vibrations, normal to the slip plane factors relating to the individual probabilities of penetration must be raised to a power *m̄p̄*, where *p̄* is the average number of exterior electrons on each atom. The electronic integrals are to be averaged over the atomic vibrations, where the energies and limits of integration depend upon atomic coordinates. Except for temperature dependence, equation (3) has the same behavior as (1), the validity of which has already been studied.

This formalism also makes clear the effect of large amounts of alloy elements on plasticity. Since the local regions of slip are considerably less orderly than the perfect crystal, in the first approximation atomic interactions can be considered to take place between pairs of neighboring atoms. If *x* is the atomic fraction of constituent *A*, and *(1-x)* that of *B*, then evidently for alloys *p̄ḡ* takes the form

$$P_{AA}\bar{g}_{AA}x^2 + 2P_{AB}\bar{g}_{AB}x(1-x) + P_{BB}\bar{g}_{BB}(1-x)^2$$

where the constants are appropriate to reactions between the various pairs of species. (In general, higher terms in  $x$  are necessary in  $p\bar{g}$ , to account for interactions with all neighbors, or where phase transformations are involved.) As a criterion of hardness that will show the same dependence upon alloy composition as Brinell number, we may take that value of stress necessary to produce a certain standard velocity of deformation  $\frac{ds}{dt} = \lambda v_{net}$ ; for which velocity we choose

the convenient value  $4\lambda\bar{v}$ , where  $\lambda$  represents the average deformation occurring with each elementary slip process. For the high local stresses associated with Brinell impressions, we replace  $\sin h\bar{p}\bar{m}\sigma$  by  $\frac{1}{2} \exp p\bar{m}\sigma$  in equation (3) and obtain

$$\sigma = \frac{P_{AA}\bar{g}_{AA} + P_{BB}\bar{g}_{BB} - 2P_{AB}\bar{g}_{AB}}{\bar{b}} x^2 + 2 \times \frac{P_{AB}\bar{g}_{AB} - P_{BB}\bar{g}_{BB}}{\bar{b}} x + \frac{P_{BB}\bar{g}_{BB}}{\bar{b}} \quad (4)$$

where  $\sigma$  is taken to be a linear function of Brinell number.

The intimate similarity between this mechanism of plastic flow and that of electrical conductivity cannot

be overlooked. In a very simple model for the latter, current is proportional to the average frequency with which electrons pass the electrostatic barriers offered by quasi-crystalline fields in the regions between adjacent atoms. Neglecting slight geometrical considerations, plastic slip of one atom past another constitutes a "relative current" of the same type; accelerating voltage being provided by the fields of displaced atomic kernels in one case, and externally applied in the other. It is to be expected that equation (3) may, therefore, also give a qualitative account of rate of current flow if the relative energy of barrier lowering,  $\bar{m}\bar{p}\sigma$  in the plastic flow case, be replaced by  $e\bar{b}'e$  where  $e$  and  $\bar{b}$  represent the electronic charge and

$$R = \frac{e}{J} = \frac{(g'_{AA} + g'_{BB} - 2g'_{AB})x^2 + 2(g'_{AB} - g'_{BB})x + g'_{BB} + 1}{8Ne^2\bar{b}'\bar{b}}, \quad (5)$$

where  $N$  is the effective density of electrons,  $\bar{l}$  the mean path length between barrier collisions, and the primed constants are related to those unprimed, above. Temperature dependence arises in the integration of parameters.

In Fig. 1 is sketched the experimental variation of Brinell hardness with composition (solid lines) for some binary systems of similar elements, and of resistivity (dashed lines), (all taken from R. F. Vines (4) except Ag-Au curve, from Mott and Jones). The pure states of the first-mentioned elements are on the left in the diagram. The parabolic character predicted by equations (4) and (5) is evident, as well as the similarity of hardness and resistivity curves for the systems Pt-Pd and Pd-Au.

Magnetism, another phenomenon to which the "relative current" principle may be applied, will be treated elsewhere.

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### Quantum-Theoretical Densities of Solids at Extreme Compression

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In no way, perhaps, is a new theory more apt to show its power and range than in extrapolation and prediction related to phenomena previously inaccessible. One example of this, applied to quantum mechanics, is the computation of the behavior of matter under extreme pressures and temperatures, particularly the well-known applications to the interior of the stars. A less well-known example is furnished by similar applications to the interior of the earth.

In recent years, Bridgman (1) has succeeded in determining the densities and compressibilities of a large number of elements and compounds up to a pressure of 100,000 atmospheres. All his values for elements and a few selected ones for compounds are plotted on the left-hand side of Figs. 1-3 in a double-

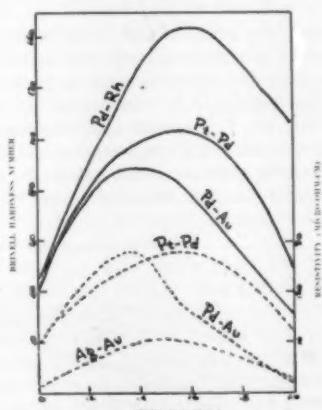


FIG. 1 (3).

be overlooked. In a very simple model for the latter, current is proportional to the average frequency with which electrons pass the electrostatic barriers offered by quasi-crystalline fields in the regions between adjacent atoms. Neglecting slight geometrical considerations, plastic slip of one atom past another constitutes a "relative current" of the same type; accelerating voltage being provided by the fields of displaced atomic kernels in one case, and externally applied in the other. It is to be expected that equation (3) may, therefore, also give a qualitative account of rate of current flow if the relative energy of barrier lowering,  $\bar{m}\bar{p}\sigma$  in the plastic flow case, be replaced by  $e\bar{b}'e$  where  $e$  and  $\bar{b}$  represent the electronic charge and

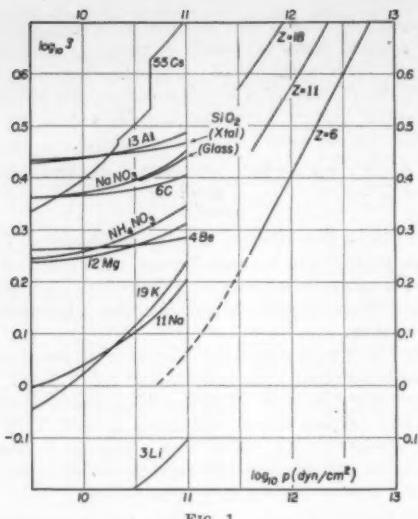


FIG. 1.

logarithmic diagram. The curves on the right are obtained from quantum theory. They are based on a Thomas-Fermi-Dirac model of the electronic density in a closest packed, cubic, monatomic lattice. The curves have been drawn mostly on the basis of the computations of Feynman, Metropolis, and Teller (2);

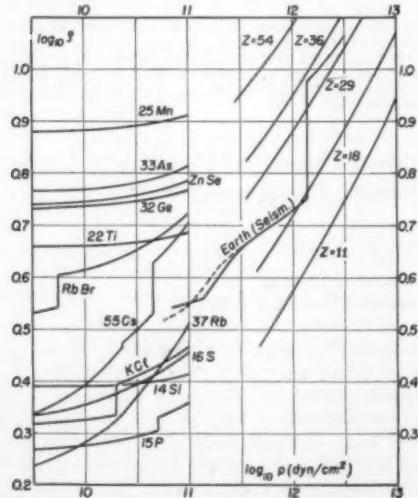


FIG. 2.

some use has also been made of the earlier results of Slater and Krutter (3), and of Jensen (4). These curves contain only one parameter, the atomic number,  $Z$ , of the constituent element. All available theoretical evidence indicates that the curve should be reasonably accurate at pressures of a few million atmospheres and

above, beginning at somewhat higher pressures for the lighter, and at somewhat lower pressures for the heavier, elements. It is fairly easy to interpolate between the measured values at low pressures, and the limiting computed values at very high pressures; the resulting uncertainty in determination of the true density should hardly exceed 15–20% anywhere.

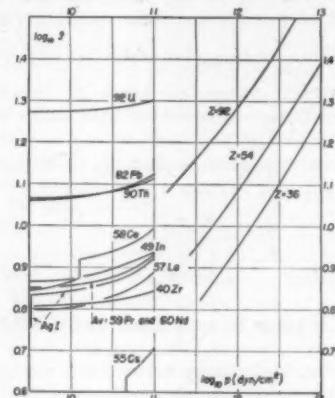


FIG. 8

These densities refer to zero temperatures, but, at a pressure of a million atmospheres and above, the internal energy of compression is so large that thermal energies are negligible in comparison, up to a few thousand degrees. Correspondingly, the expansion at melting is very small at these pressures, and the curves should also be applicable to such substances as molten iron, assumed to exist in the earth's core.

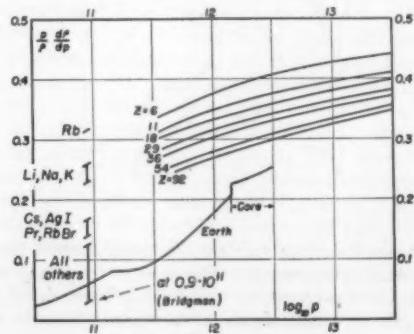


Fig. 4

In Fig. 2 there also is shown a curve, representing the density variation inside the earth, computed by Bullen (5) from seismic data. The dashed part shows a modification proposed by Gutenberg (6). It is seen that the curve corroborates the usual assumption that the earth's outer part, the mantle, consists mainly of silicates, whereas the central part, the core, consists of iron. It is extremely difficult to reconcile this curve

even qualitatively with any other assumption about the earth's constitution that is consistent with the known cosmic abundance data of the elements (7, 8). In particular, the assumption of Ramsey (9) that the earth's core consists of silicates seems to be excluded, and still more so the suggestion that the earth's interior contains large amounts of compressed hydrogen.

Fig. 4, finally, shows the quantity  $d \ln \rho/d \ln p$ , essentially the compressibility, as a function of the pressure. The figure conveys the suggestion that Bullen's values for the earth might have to undergo some slight adjustments to agree better with the curves

obtained by joining the experimental data to the high-pressure part of the theoretical data.

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## News and Notes

### The International Oxford Conference on Nuclear Physics

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THE INTERNATIONAL NUCLEAR PHYSICS CONFERENCE took place in historic Oxford last September 7-13. Sponsored by the British Ministry of Supply, it was organized—and excellently so—by the British Atomic Energy Research Establishment (AERE). About 200 physicists participated; half of them came from British universities, about 30 from AERE itself, nearly as many from America, and approximately 40 from the European continent. Pontecorvo's name was in the list of participants, but actually he was not present. There was no direct delegation from behind the Iron Curtain.

Most of those who came alone were housed in Brasenose College, Oxford; the couples were pleasantly quartered in the country in a palatial house provided by the Ministry of Supply. A guided tour through the AERE Laboratories at Harwell made a deep impression on many of us. In spite of the very much smaller funds at the disposal of the British counterpart of the U. S. Atomic Energy Commission, and in spite of the shorter history of the British atomic energy program, one sensed the stability of the organization, the permanency of the installation, and the well-settled personal relations within the AERE Laboratories. The scientific and technical accomplishments of the Harwell Laboratory are quite impressive. It was also refreshing to find its director, Sir John Cockcroft, participating in the whole conference.

The principal subjects of the conference were high-energy physics, physics of light nuclei, reactor physics, and theory. Naturally this summary will be only illustrative of the subjects discussed and can cover only a few examples to show the type of results presented. Not even examples will be given of the discussion of experimental techniques and apparatus.

Several new and important results were announced on the high-energy program. Moyer described the experiments (Steinberger and Bishop, Berkeley) which led to the discovery of the neutral  $\pi$  meson. The mass of this particle is slightly lower than that of the charged  $\pi$  mesons; it is about 265 against 275 electron masses. Evidence was presented that its lifetime is very short: in about  $2 \times 10^{-12}$  seconds it disintegrates into two light quanta. Experiments proving the existence of the neutral  $\pi$  mesons and their disintegration were presented also by King (Bristol).

New data were presented also on the high-energy proton-proton and proton-neutron scattering, originating in Berkeley, AERE, Rochester, and Harvard. The cross section for a collision between a neutron and a proton is considerably smaller than that for a collision between two protons. The latter cross section seems to depend very little on energy in the high-energy region, and the collision appears to be spherically symmetric. Its absolute value is around  $4.5 \times 10^{-27} \text{ cm}^2$  per unit solid angle. These data were discussed by Pais (Princeton) from the theoretical point of view. He showed that, assuming a spin-orbit type of interaction, it is possible to explain the data in such a way that the interaction is, fundamentally, the same between a proton-neutron and a proton-proton pair. The difference in the actual cross section arises from the Pauli exclusion principle (Case and Pais).

Professor Blackett (Manchester) presented evidence for mesons of about 800 electron masses.

Level schemes for several nuclei, including  $\text{Li}^7$ ,  $\text{Be}^7$ ,  $\text{O}^{16}$ ,  $\text{C}^{12}$ , and  $\text{O}^{17}$ , were presented in the session on light nuclei. Some of these apparently showed remarkable regularities which are not understood. Extensive data were given also on the reactions of the various hy-

drogen and helium isotopes with each other. Alvarez described experiments to produce new high-energy radioactive nuclei, such as  $N^{12}$ ,  $N^{17}$ , and  $Na^{20}$ . The disintegration of these nuclei produces delayed protons and  $\alpha$ -particles, which follow the original  $\beta$ -disintegration much in the same way as the delayed neutrons follow the  $\beta$ -disintegration accompanying fission. There was also an extended session on angular distributions and angular correlations, the investigation of which promises to solve many a problem that could not be tackled previously.

The theoretical session was mainly devoted to the discussion of the nuclear shell model, in particular the  $j-j$  coupling scheme proposed by M. G. Mayer and Haxel, Jensen, and Suess. The last address was given by Dirac on his new field theory. It was a most inter-

esting occasion: apparently none of the participants could follow Dr. Dirac's new ideas in detail. Nevertheless all realized that important new physical principles are in the course of being formulated.

As mentioned, the organization of the conference was excellent. The discussion was lively throughout, to the point, and never protracted. Perhaps the most remarkable accomplishment of the organizers was, however, a 115-page report of the proceedings of the conference. This was mailed out to the participants a little more than two weeks after the conclusion of the meeting. It contained a remarkably accurate summary of all the addresses and most of the discussion, even of the highly technical and "theoretical" remarks. It was the result of the work of several members of the AERE and was edited by E. W. Titterton.

## Scientists in the News

**G. Robert Coatney** has assumed the editorship of the *Journal of the National Malaria Society*. Manuscripts intended for publication in the *Journal* should be sent to Dr. Coatney, Laboratory of Tropical Diseases, National Institutes of Health, Bethesda 14, Md.

**Alonzo G. Grace** has been appointed to head a new Division of Advanced Study in New York University's School of Education. Formerly on the faculty of the Department of Education of the University of Chicago, he was for ten years Commissioner of Education for Connecticut, resigning in 1948 to become the first director of the Education and Cultural Relations Division of the American Military Government in Germany.

**James M. Hundley** has been appointed consultant on nutrition in the Office of Health Resources of the National Security Resources Board. Dr. Hundley will advise on problems of food and diet in relation to total defense planning. He has been a member of the staff of the National Institutes of Health, PHS, since 1943 and is chief of the Nutrition Section of the recently created National Institute for Arthritis and Metabolic Diseases.

Los Alamos Scientific Laboratory of the University of California has announced two recent additions to the staff. They are **William E. Keller**, a research chemist formerly associated with the Ohio State University Research Foundation, who will work with the laboratory's Chemistry and Metallurgy Division, and **Rodney H. Foss**, formerly at Yale University's Sterling Chemistry Laboratory, where he had been working for his Ph.D. in organic chemistry, who will head the biochemistry section of the Biomedical Research group.

Changes in membership of the Committee on Navigation, Department of Defense Research and Development Board, were announced recently. **Frederick B. Lee**, Civil Aeronautics Administration, has been appointed a member to represent the Department of

Commerce; he succeeds **Delos W. Rentzel**, whose deputy he has been. **David D. Thomas**, has been named Mr. Lee's deputy. **L. F. Dodson** has been named a Navy member to succeed **Robert C. Sutliff**.

## Meetings and Elections

A symposium on Molecular Structure and Spectroscopy, sponsored by the Graduate School and the Department of Physics and Astronomy at the Ohio State University and by the Division of Chemical Physics of the American Physical Society, will be held at the University, June 11-15. There will be discussions of the interpretation of molecular spectroscopic data, as well as of methods of obtaining such data. In addition, there will be sessions devoted to those phases of spectroscopy of current interest. For further information or for a copy of the program when it becomes available, write to Professor Harald H. Nielsen, Department of Physics, Ohio State University, Columbus 10.

The recently chartered Institute of Cancer Cytology has elected the following officers: president, Arthur Purdy Stout, Columbia University, and a member of the Educational Committee of the American Cancer Society; vice presidents, Herbert F. Traut, University of California; Emil Novak, Johns Hopkins Hospital; Charles D. Read, University of London; J. Ernest Ayre, McGill University; and K. Sheldon MacLean, Roosevelt Hospital, New York; chairman of the board, F. Bayard Carter, Duke University. The principal aims of the international organization are to endorse, and to aid in developing, regional cytology centers and to popularize the utilization of the cytologic test for cancer. These centers will provide educational and training facilities for local and visiting physicians and technicians.

The 7th Annual Conference on Protein Metabolism, sponsored by the Bureau of Biological Research at Rutgers, in cooperation with FAO, is considering (January 26-27) these phases of the subject: Gastrointestinal dynamics and utilization of protein, folic

acid and vitamin B<sub>12</sub> in relation to amino acids, specific amino acids in relation to water-soluble vitamins, mineral metabolism and tissue protein synthesis, protein metabolism, clinical aspects of protein malnutrition, and protein metabolism as affected by food shortage. Ernest Geiger, J. A. Stekol, Robert R. Sealock, Paul R. Cannon, M. Macheboeuf, Hugh M. Sinclair, and Ancel Keys are participating.

The 1950-51 Jesup Lectures, sponsored by the Department of Zoology, Columbia University, will be given by John Runnström, of the University of Stockholm. The subject will be "Developmental Physiology of the Sea Urchin," and the dates are February 14, 16, 21, 23, 28, and March 2, 7, 9.

## Grants and Awards

The American Society of Photogrammetry's award for outstanding work in its field was presented to Russell K. Bean during the society's recent annual convention. Chief of the photography section of research and engineering control, Topographical Division, U. S. Geological Survey, Mr. Bean was honored for his design of a twinplex system of mapping photography, which gives greater accuracy with fewer pictures.

The Chemical Arts Company of Chicago, a teenage concern manufacturing decorative Christmas candles, has won the third annual Chemistry Products Award, given by *Chemical and Engineering News* to honor the nation's outstanding Junior Achievement group in the chemical field. The award, a bronze plaque, will be presented by Walter J. Murphy, editor of the ACS journal, at a dinner to be held by the society's Chicago Section February 23. June E. Stinnett, sixteen-year-old president of the company, will accept the plaque. Individual certificates also will be conferred on Miss Stinnett and the 14 other members of the company, which was selected from among more than 100 competing groups by the editors of *C&EN* and a committee of leading industrialists. The winning company was sponsored by the Peoples Gas, Light & Coke Company, Chicago.

The Theobald Smith Award of \$1,000 and a bronze medal, which has been given yearly since 1937 (except for a lapse during the war years) by Eli Lilly and Company, of Indianapolis, under the auspices of the AAAS, was not given during the recent meeting of the Association because of an unavoidable delay in calling for nominations. Nominations are now being requested, however. They may be made by Fellows of the AAAS and should be sent to the secretary of the Subsection on Medicine (Dr. Gordon K. Moe, Department of Physiology, State University of New York Medical Center, Syracuse, N. Y.). Nominations should be accompanied by full information concerning the nominee's personality, training, and research work. The prize is given for "demonstrated research in the field of the medical sci-

ences, taking into consideration independence of thought and originality." The research is not to be judged in comparison with the work of more mature and experienced investigators. Any investigator who was less than thirty-five years of age on January 1, 1950, and is a citizen of the United States is eligible. Nominations must be received before March 15. The secretary requests that all data be submitted in triplicate. The president of the Association and four Fellows will form the committee of award, and the winner will be announced early in May. Past recipients: 1937, Robley D. Evans, MIT; 1938, Charles F. Code, The Mayo Foundation; 1939, Albert B. Sabin, Children's Hospital Research Foundation, Cincinnati; 1941, Herald R. Cox, Lederle Laboratories, Inc.; 1943, Sidney C. Madden, Brookhaven National Laboratory; and 1949, Seymour S. Kety, Graduate School of Medicine, University of Pennsylvania.

## Fellowships

Tau Beta Pi has announced its annual program of fellowships for graduate study in engineering for the school year 1951-52. The amount available for each fellowship is \$1,200 payable in ten monthly installments, and in some cases the society has arranged with schools to remit tuition. For additional information write Paul H. Robbins, Director of Fellowships, 1121 15th St., N.W., Washington 5, D. C. Applications must be received by February 28.

The Oak Ridge Institute of Nuclear Studies has been named administrator of the AEC predoctoral and postdoctoral fellowships for 1951-52. Tentatively planned are: predoctoral fellowships, up to 150 in the physical sciences and up to 100 in the biological sciences; postdoctoral, up to 30 in the physical sciences and up to 45 in the biological sciences. Predoctoral fellows will receive a basic stipend of \$1,600, and postdoctoral fellows \$3,000, with an additional \$500 if married, plus \$250 for each child not exceeding two. Additional allowances will be made for travel and tuition. Application forms and other information may be obtained from the Oak Ridge Institute of Nuclear Studies, University Relations Division, Box 117, Oak Ridge, Tenn. Applications must be received by February 15.

The Institute of Medicine of Chicago announces that the Jessie Horton Koessler Fellowship for aid in research in biochemistry, physiology, bacteriology, and pathology has been re-awarded for 1950-51 to Charlotte Robertson, to continue her work on the loss of sensitivity to stimulation by cholinergic drugs manifested by denervated sweat glands, and to begin an investigation of the histamine content of various body secretions under the direction of Andrew C. Ivy, Department of Clinical Science, University of Illinois.

The New York Zoological Society again announces grants-in-aid available for the research program at its Jackson Hole Research Station. The fifth summer

program will include studies in ecology, animal behavior, and land management. Further information may be obtained by addressing Director, Jackson Hole Research Station of the New York Zoological Society, Moran, Wyo.

## Colleges and Universities

The new Research Laboratory for Diseases of Dogs has opened at Cornell University. The center is especially designed for the study of viruses, which are believed to cause many of the contagious diseases. A main laboratory building contains the latest in isolation facilities for the controlled study of dog diseases. The center also has a separate kennel for rearing a disease-free dog colony. A staff of 20, including 5 veterinarians, under the direction of James A. Baker, is already conducting studies on infectious hepatitis, leptospirosis, and encephalitis. In general, the research will deal with fundamental aspects of disease from the point of view of prevention rather than cure.

A new research foundation has been established at Fordham University to coordinate present research and to stimulate original studies in the arts and sciences. Researchers at the university have recently developed a high-temperature, light-weight refractor material for the Air Materiel Command at Wright Field, Dayton, Ohio. Other projects now being conducted include those for the ONR, Damon Runyon Cancer Fund, Research Corporation, USPHS, and the AEC.

A new Blood Characterization and Preservation Laboratory was dedicated January 8 in Harvard University's Bussey Institution of Applied Biology. The new laboratory, under the direction of Edwin J. Cohn, is an emergency establishment to accelerate the development of new methods for use in the National Blood Program.

## Deaths

**Harry G. Haskell**, a director and former vice president of E. I. du Pont de Nemours & Co., died January 4 at 80. Starting with Du Pont in 1893 as a clerk, he became director of the high-explosives operating department during World War I. He retired in 1946.

The founder of Columbia University's Department of Industrial Engineering, **Walter Rautenstrauch**, died recently at the age of 70. Dr. Rautenstrauch was a key figure in the "Technocracy" movement during the depression, and his later defection helped to end the movement. He was the author of 14 books on economics and engineering. His most recent work, *Budgetary Control*, which he wrote with Raymond Villers, was published in September.

**Albert S. Howell**, co-founder of the Bell & Howell Company, manufacturers of motion-picture and photographic equipment, died January 3 in Chicago at 71. Early inventions by Mr. Howell were credited with eliminating the "flicker" in motion pictures and

with providing a way for additional copies of films to be made cheaply. These inventions were a film perforator, a continuous printer, and a standard camera with precise film-moving mechanisms.

**Alfred Hume**, chancellor emeritus of the University of Mississippi, died December 25 at 84. Starting as a professor of mathematics in 1890, he was chancellor three times during his 58 years of teaching.

## Miscellaneous

The Registry of Rare Chemicals, 35 West 33rd St., Chicago, submits the latest list of wanted chemicals: bromogermane; bromosilane; iron pentacarbonyl; silicon bromotrifluoride; silver peroxide; sym-tri(trifluoromethyl)benzene; 3,3,3-trifluoropropene; benzoithiophene; 1-chloro-3,5-dimethylbenzene; methyl stearyl ketone; 4-hydroxy coumarin; D-monochlorosuccinic acid; Ethyl-*b,b*-diethoxypropionate; p-hydroxyhippuric acid; 1,3-diphenylbenzofuran; uramildiacetic acid; ferritin; toxisterol; L-xylulose; and hexokinase.

An International Commission for Plant Slide Exchanges has been established by the Botanical Section of the International Union of Biological Sciences in cooperation with the California Botanical Materials Company. The aim of the commission is to enable cooperating institutions and individuals to build up reference slide collections by exchanging plant material sent in by them for slides processed either from these materials or from those forwarded by others. Information may be obtained from Dr. D. A. Johansen, Chairman, International Commission for Plant Slide Exchanges, 861 East Columbia Ave., Pomona, Calif.

The Technical Command at Army Chemical Center, Md., has openings for approximately 60 professional employees. Analytical, organic, inorganic, and physical chemists, meteorologists, physicists, chemical engineers, mechanical engineers, statisticians, and draftsmen are needed immediately for work on various research and development projects for new chemical and radiological warfare agents and materiel. The salary range is from \$8,100 to \$7,400. Interested applicants may apply on Standard Form 57, or in person, to the Civilian Personnel Office, Army Chemical Center, Md.

## Publications Received

*Guide to the Classification of Fishing Gear in the Philippines*. Augustin F. Umali. Fish and Wildlife Service Research Report 17. U. S. GPO, Washington, D. C. 40¢.

*Raccoons of North and Middle America*. Edward A. Goldman. North American Fauna 60. Fish and Wildlife Service, U. S. GPO, Washington, D. C. 45¢.

*Bulletin on Narcotics*. Vol. II, No. 2. U. N. Dept. of Social Affairs, Lake Success, N. Y.

*Ten Years of Progress—Illinois Institute of Technology*. Technology Center, Chicago 16.

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When you pick up an Eastman Organic Chemical bottle these days, you see a new label that gives the structural formula and the formula weight. We're pretty sure you'll find it helpful in eliminating the confusion over identity and position of groupings that often arises from variations in nomenclature. It should also save you the time required to look up or calculate molecular weight.

A white label indicates "Eastman" grade, the highest in purity. Yellow means "Practical" grade, sufficient in purity for most laboratory synthesis. A blue label ("Technical") goes on high-grade commercial compounds.

The purity of the more than 3400 Eastman Organic Chemicals is actually checked in many ways, but a statement of melting or boiling ranges, obtained by actual measurement in our control laboratory, is what we believe to be most generally informative. That's the way we do it in our catalog. The latest issue is List No. 37. If you don't have a copy, you'll do well to send for it without delay. Write *Distillation Products Industries*, Eastman Organic Chemicals Department, Rochester 3, N. Y. (Division of Eastman Kodak Company.)



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Also...vitamins A and E...distilled monoglycerides...high vacuum equipment

# What GENERAL ELECTRIC People Are Saying

W. R. G. BAKER

*Vice President, Electronics Department*

**CIVIL DEFENSE:** No longer do oceans and distance protect us from any determined and ruthless enemy who possesses atomic weapons. Are we then tilting at windmills if we take precautions to eliminate surprise, confine the damage, and alleviate sufferings of the wounded? I sincerely think not.

We maintain police and fire departments, and do not rebel at the expense because there are no holdups or fires. Can anyone who has lived through the years after the war and watched the march of Communism in Europe and Asia say that we are not in real danger? The communities . . . should seize the initiative in planning on a local level for . . . protection of their citizens against not only the threat of atomic weapons but other disasters resulting from sabotage, fire, flood, or pestilence.

We should accept this responsibility, not through fear, but because we are men enough, American enough, to recognize and face grim reality, and deal with the problem of safeguarding our families and our neighbors.

*Utica, New York  
November 13, 1950*



K. C. SEEGER

J. H. OLIVER

*Apparatus Department*

**RADIANT CHICKEN BROODING:** Repeated tests in the midwest, in New York State, and at the University of Delaware have proved that high air temperatures are not necessary for the successful brooding of chicks, provided they receive sufficient radiant energy to keep them warm. These conclusive tests were carried to the extreme of brooding baby chicks in air temperatures of 15° F below zero. In this extreme test, 30 chicks were placed in a cold storage plant where air temperatures are maintained at 5° to 15° F below zero. At the end of two weeks, the 30 chicks, all alive, were larger, 1.9 pounds per 100 heavier, and better feathered than others of the same hatch, which were brooded in the conventional manner in a warm room under coal stove brooders.

Four 250-watt infrared lamps . . . 18 inches above the litter . . . supplied the radiant energy that kept them comfortable at all times. Radiant energy at chick level measured 2.62 btu per square inch. This heated the chicks but contributed little heat to the jars of water, so that half of the water in the jars was frozen.

*American Society of Agricultural Engineers  
Chicago, Illinois  
December 18, 1950*



J. W. RAYNOLDS

*Chemical Department*

**SILICONES:** The first silicone rubbers were useful because of the high and low temperature stability, together with good oil resistance, ozone resistance, and considerable chemical resistance. From a rubber man's viewpoint, silicone rubber was miserable to handle. It would not bond on the mill. Pigments and fillers were difficult to combine. Curing temperatures ranged up to 400° F with time cycles up to 72 hours . . .

During the past year, our research and development engineers have been making steady progress in perfecting some new silicone rubber polymers and compounds. These new materials look, feel, and handle more like the natural rubber products. They also possess the excellent high and low temperature characteristics for which silicone rubbers are especially noted.

The new silicone rubber has over twice the elongation and tensile strength of the old product. It handles easily on a cool rubber mill. It can be calandered, extruded, or molded by compression, transfer, or injection processes, and has curing cycles as short as one minute at 300° F.

*American Chemical Society  
Los Angeles, California  
November 7, 1950*

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**GENERAL  ELECTRIC**



Gives quantitative basis for making operational decisions

## METHODS of OPERATIONS RESEARCH

By PHILIP M. MORSE, *The Massachusetts Institute of Technology* and GEORGE E. KIMBALL, *Columbia University*. Shows how the techniques of this recently developed science can be applied to help make decisions in many fields—scientific, industrial, military, governmental. It differs from the usual statistical analysis in that the final aim is to predict future operations and to understand them well enough to modify them to produce new or better results. Presenting a careful definition of the science and an explanation of the tools to be used, the authors discuss the setup of an operations research group in some detail. *A Technology Press Book, M.I.T.* January 1951. Illus. 158 pages. \$4.00.

All aspects covered  
by 13 area specialists

The first critical review

Emphasizes x-ray study of crystals  
—features correlation diagrams

## GEOGRAPHY of the PACIFIC

Edited by OTIS W. FREEMAN, *Eastern Washington College of Education*, with 13 contributors. Written by geographers, anthropologists, and other Pacific area experts, this book gives an up-to-date picture of the ocean, the islands, the people, the resources, the industries, and the other factors that make up the geography of this vitally important area. January 1951. 573 pages. 170 illus. College edition—\$8.00.

## The FISCHER-TROPSCH and RELATED SYNTHESES Including a Summary of Theoretical and Applied Contact Catalysis

By HENRY H. STORCH, NORMA COLUMBIC, and ROBERT B. ANDERSON, all with *U. S. Bureau of Mines*. Reviews the tremendous amount of scientific and engineering data on synthesizing aliphatic organic compounds by the catalytic hydrogenation of carbon monoxide. March 1951. Approx. 603 pages. 183 illus. Prob. \$8.50.

## ELEMENTS of OPTICAL MINERALOGY An Introduction to Microscopic Petrography Part II—DESCRIPTIONS of MINERALS With Special Reference to Their Optic and Microscopic Characters

Fourth edition by ALEXANDER N. WINCHELL, *University of Wisconsin*, with the collaboration of HORACE WINCHELL, *Yale University*. Offers a description of minerals whose optical qualities are sufficiently well known to permit diagnosis by means of a microscope. January 1951. 551 pages. 427 illus. \$12.50.

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**Garneau RECORDING  
PSYCHOGALVANOMETER**

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For clinical and experimental investigation of disorders involving sympathetic reaction, such as pain reflexes. In the psychological laboratory, the instrument has a well-known application as a so-called "lie detector". Resistance is read directly from a calibrated dial. Small variations, greatly magnified, are shown on the meter. Battery operated. Price .... \$115.00

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New Address—SOUTH WOODSTOCK, VERMONT, U.S.A.  
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Specialists in Microscopic and Photographic Equipment



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3. Closing Date: Advertisements must be received by SCIENCE, 1515 Mass. Ave., N.W., Washington 5, D.C., together with advance remittance, positively not later than 14 days preceding date of publication (Friday of every week).

## POSITIONS WANTED

Assistant Bacteriologist—New York City only. Capable, experienced technician. Can work alone or under direction. Several years experience in techniques of antibiotic production (fermentations), level determinations, and general bacteriological procedures. Box 403, SCIENCE. X

Bacteriologist-mycologist physician age 36, M.S., Ph.D., M.D. all leading universities. Laboratory and clinical research experience, publications. Available July. Box 404, SCIENCE. X

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Chemist; Ph.D. (Physical, Organic, Analytical); five years, research department of industry; considerable experience atomic energy; for further information, please write Science Division, Medical Bureau (Burneice Larson, Director) Palmolive Building, Chicago.

Economic Entomologist, M.S. desires position, 20 years experience with Administration, important corporation in the fields of insecticides, fungicides, field tests, field representation, insect control. Box 409, SCIENCE. X

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Organic Chemist: Age 36, German, Ph.D. (Munich), 10 years research experience, 9 publications and several patents, desires position in industry or university. Box 406, SCIENCE. X

Physicist, M.S.; Nine years diversified research in electronic physics and communications. Wishes to apply experience to biophysical problems in audiology. Academic or Medical research institute preferred. Box 407, SCIENCE. X

**YOU reach over 32,000 scientists in  
these columns—at a very low cost**

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Biochemist. Clinical Laboratory, large north-central University Hospital requires biochemist competent to supervise adequate technical staff. Experience with newer methods, including flame-photometry, essential. Salary \$5,000.00. Box 402, SCIENCE. 1/26.

Biochemist Technician, (female) for studies with microorganisms and bacteriophage in industrial research laboratory. In reply give experience, references and salary expected. Box 401, SCIENCE. 1/26.

# PERSONNEL PLACEMENT

## POSITIONS OPEN

### Positions Open:

(a) Electron Microscopist; eye research laboratory, university medical center; East. (b) Protein Chemist; research laboratories, medical school; East. (c) Biochemist with strong background in histology; research post, industrial company, Chicago. (d) Mycologist and Virologist; physicians of outstanding attainments, qualified for professorial appointments. (e) Physician or Ph.D. in pharmacology, physiology or biology; duties administrative including clinical research; pharmaceutical industry; opportunity of becoming medical director; East. (f) Neurophysiologist, Ph.D., with extensive experience; physiologist, Ph.D. with minor in endocrinology or pharmacology and, also, two physiologists with Bachelor degrees; research department, new psychiatric unit, large teaching hospital; medical center. S-1—Science Division, Medical Bureau (Burneice Larson, Director) Palmolive Building, Chicago. X

## RESEARCH ASSOCIATE

Opening in large Eastern Pharmaceutical Company for Research Associate Ph.D. or Sc.D. in bacteriology or biochemistry with an immuno-chemical background to direct studies on antigen separations and purifications. Please forward resume including age, experience and salary desired to

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For proof service on *display* ads complete "copy" instructions must reach the publication offices of SCIENCE, 1515 Massachusetts Avenue, N.W., Washington 5, D.C., not later than 4 weeks preceding date of publication.

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### METHODS FOR THE STUDY OF THE INTERNAL ANATOMY OF INSECTS

This volume covers the dissection, staining and mounting of the internal organs and tissues of insects. Its special merit is a precise organization of text material making it a beginners' book for simple easy use. The fixatives, stains and mounting media are the simplest possible for results to be obtained. A long use of over 25 years on hundreds of insect species has proven its basic value. The price has had to be raised to \$3.00 post paid.

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Department of Zoology and Entomology, Ohio State University, Columbus 10, Ohio, U.S.A.

# The MARKET PLACE

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Send us your Lists of SCIENTIFIC BOOKS AND PERIODICALS which you have for sale. Complete libraries; sets and runs; and single titles are wanted. Also please send us your want lists.

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are needed by our library and institutional customers. Please send us lists and descriptions of periodical files you are willing to sell at high market prices. J. S. CANNER, INC., Boston 19, Mass. (Dept. A3S).

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Sets and runs, foreign and domestic  
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of the Cleveland Meeting?

A limited number of the General Program of the 117th AAAS Meeting recently held in Cleveland is available.

With 304 pages, the Program is also a Directory of all Sections and affiliated societies of the Association.

You will find it invaluable for reference. If you don't already have a copy, order yours now—\$1.00 per copy, prepaid.

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# The MARKET PLACE

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Universities and Colleges throughout the United States continue their great demand for recommendations for those trained in the different fields of Science. The positions range from instructorships to heads of departments.

Our service is nation-wide.

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albino farms • P. O. BOX 331  
RED BANK, N. J.

### ANIMAL CAGES AND ACCESSORY EQUIPMENT

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HOELTGE BROS., Inc.

1919 Gest St. Cincinnati 4, Ohio  
Write for 1950 Catalog

### WHITE RATS 40c and up

Rabbits, Cavies, White Mice, Ducks, Pigeons, Hamsters  
Write • J. E. STOCKER • Ramsey, N. J.

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- Range 1.400-1.700, intervals of 0.002, or as selected
- Index Certified to  $\pm 0.0002$
- Range 1.71-1.83, intervals of 0.01

Write for Price List Nd-S  
R. P. CARGILLE 118 Liberty Street, New York 6, N. Y.

### STAINS

STARKMAN Biological Laboratory

RARE COMMON  
Price list on Request  
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Toronto, Canada

 **FIALA OUTFITS, INC.**  
10 WARREN STREET, NEW YORK 7, N.Y.  
SCIENTIFIC INSTRUMENTS & FIELD EQUIPMENT  
FOR GEOLOGISTS, SURVEYORS, ENGINEERS & EXPLORERS  
Every necessity suggested, supplied as required  
by experience in the field, from fields to the laboratory  
INCORPORATED 1928

(The Market Place is continued on page 16)

## SCIENCE AND TECHNOLOGY

Periodicals in German and French

War year issues of 140 medical, scientific, and technical periodicals.

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Volumes and issues of recent American out-of-print medical journals.

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Over 700 titles including reprints of German books, many of which were published during the war.

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Ann Arbor

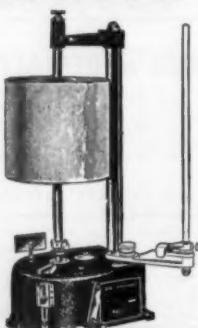
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## Bird SPRING DRIVEN KYMOGRAPH

• SIMPLE TO OPERATE

• ECONOMICAL TO OWN

• PRECISION DESIGN



Speeds from 3 cm. to 500 cm. per minute.  
Can be rewound while in operation without disturbing speed.

WRITE:

Phipps & Bird  
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## The MARKET PLACE

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Lists more than 300 items for Research—  
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CHAGRIN FALLS, OHIO



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- Clean healthy well-fed animals
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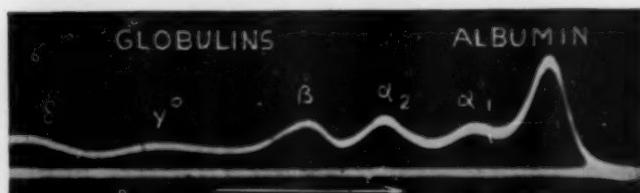
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